Connecting the EM and GW Skies: What We've Managed To Do So Far

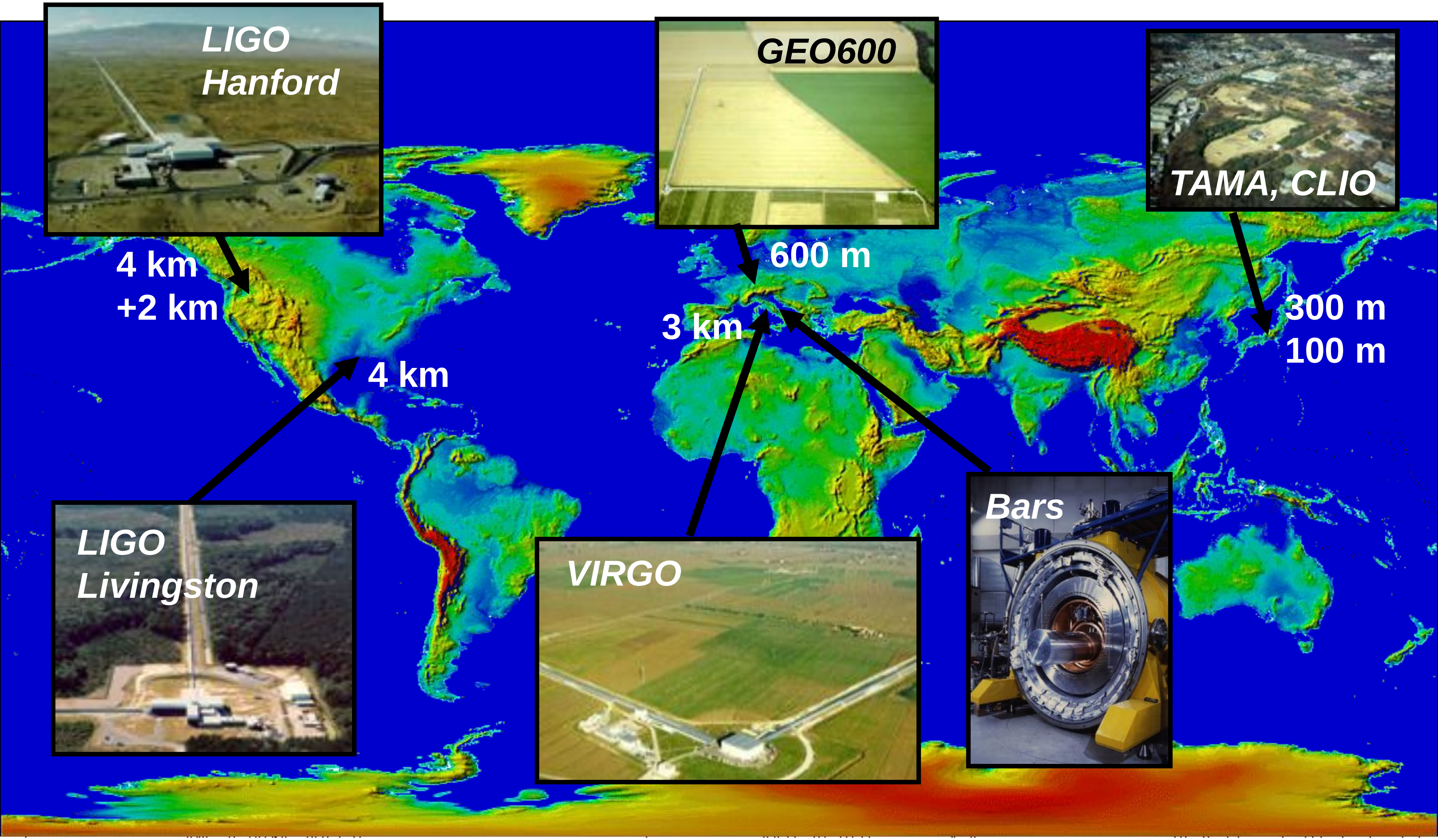
Peter Shawhan (U. of Maryland / JSI)
for the LIGO Scientific Collaboration
and Virgo Collaboration

Princeton Center for Theoretical Science
April 30, 2012

LIGO-G1200457-v5

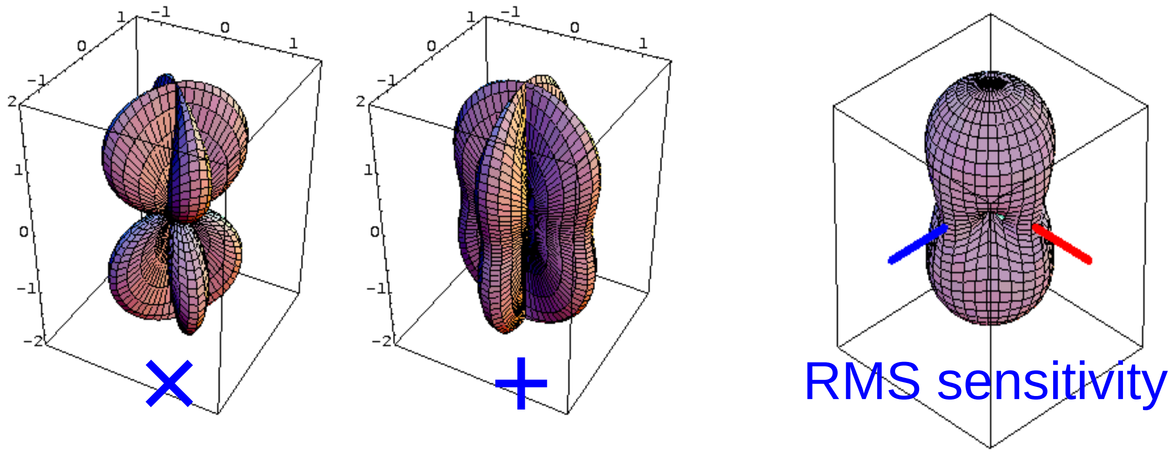
GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

The Global GW Detector Network in the Recent Past



Basic Properties of GW Detectors

Weakly directional, and polarization-sensitive



All detectors generally will respond to an arriving GW signal

“Pointed” by network analysis software

Can in principle operate 24/7 monitoring whole sky

In practice, have achieved ~70-90% (per detector) during science runs

All raw data is archived

Enables after-the-fact searches for signals from astrophysical events

How EM-GW Connections Can Help

EM observations guide GW data analysis

Known transient events: GRBs, SGR flares, core collapse supernovae, pulsar timing glitches, unusual optical transients, …

- ➔ Known event time and sky position permits deeper GW search
- ➔ Event type suggests what kind(s) of GW signal to look for

Known or presumed rapidly-rotating neutron stars: pulsars, SN remnants

- ➔ EM data indicates (or at least suggests) source location and signal parameters, allowing coherent search with long integration time

GW event candidates guide EM observations

Escalate importance of already-observed EM events ➔ Observe further

EM follow-up observations (prompt and/or delayed)

- ➔ May catch a counterpart that would have been missed, or detected only later

Interpretation of jointly detected events

Or interpretation of *non*-detection in GW or EM

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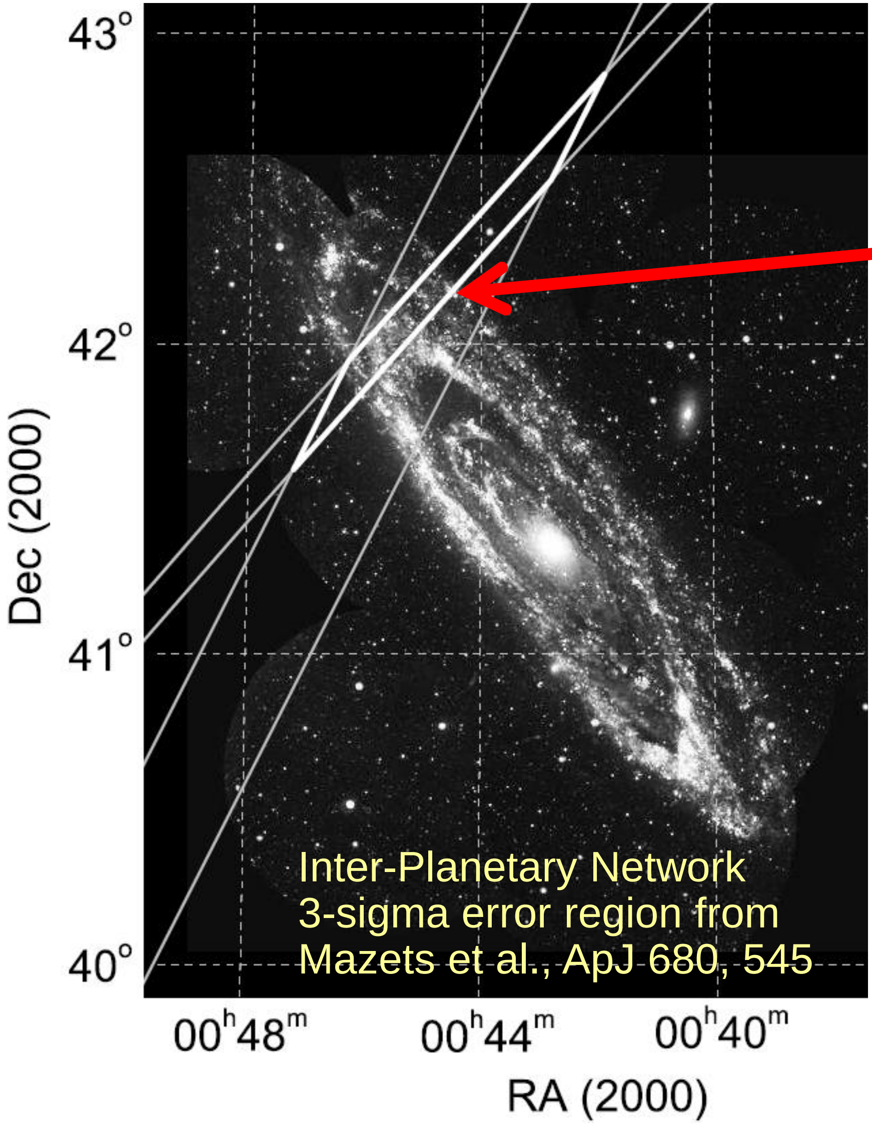
Example: GRB 070201



Short, hard gamma-ray burst

Leading model for short GRBs: merger involving a neutron star

Consistent with being in M31

Both LIGO Hanford detectors were operating

Searched for inspiral & burst signals

No plausible GW signal found ➔ very unlikely to be a merger in M31

Abbott et al., ApJ 681, 1419 (2008)

Consistent with SGR giant flare in M31

Similar analysis done for GRB 051103

Abadie et al., ApJ submitted, arXiv:1201.4413

Systematic GRB–GW Searches

Most recently, analyzed 155 GRBs reported via GCN during 2009-10 while 2 or 3 LIGO/Virgo detectors were taking good data

GW "burst" search

Done for 151 GRBs

Coherent burst search allowing for arbitrary GW waveform

Assumed circular polarization since rotational systems are efficient GW emitters and the γ rays are believed to be beamed

Compact binary coalescence search

Done for 26 short or "short-like" GRBs

Coherent matched filtering search for inspiral waveforms from a binary with at least one neutron star

Preprint to appear on arXiv soon

Earlier science runs: *Abbott et al., PRD 77, 062004 ; ApJ 715, 1438 ; ApJ 715, 1453*

Space and Time Windows

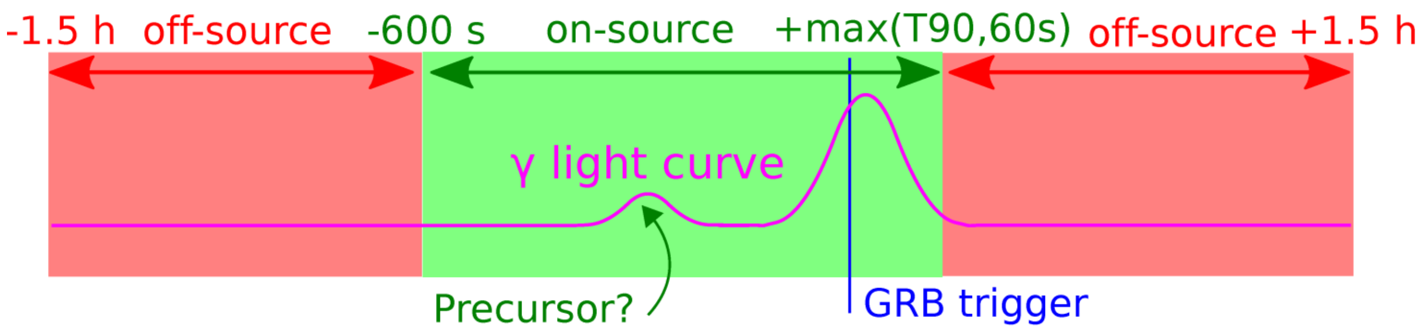
Searched over sky region reported for the GRB

GRBs reported by *Swift* and other satellites are generally well localized

GRBs detected by Fermi GBM have large error regions

Time window allowed for relative time offset from GRB trigger

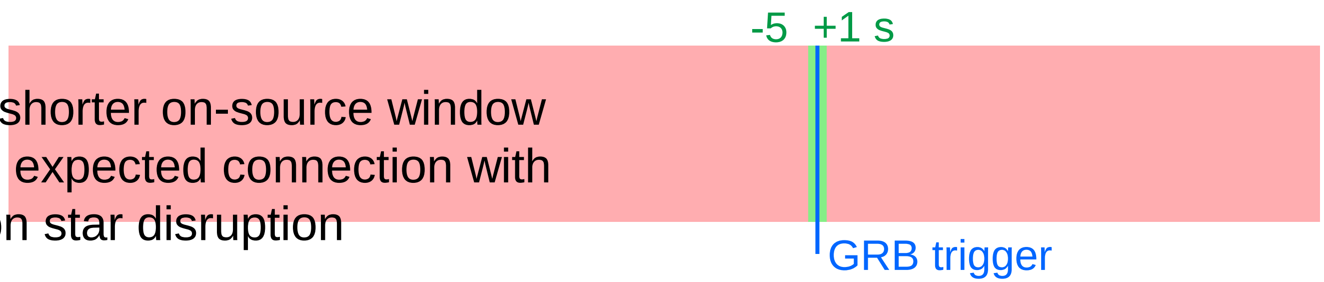
Burst:



Generous "**on-source**" window allows for seen or unseen precursor

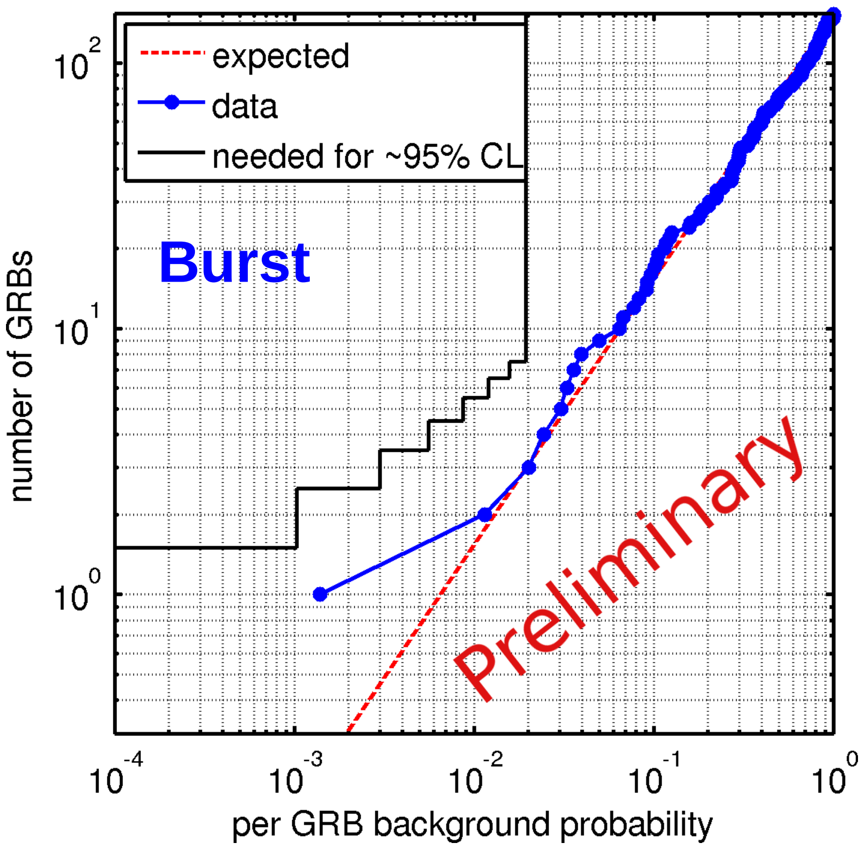
e.g. GRB 060124 precursor was 570 s early *[Romano et al. 2006]*

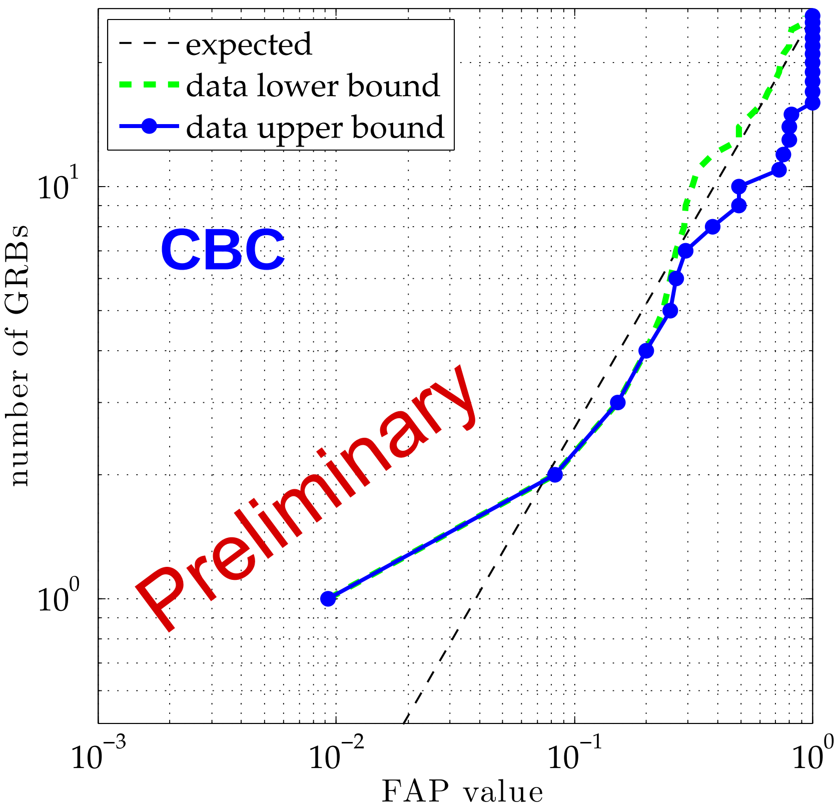
CBC:



Much shorter on-source window due to expected connection with neutron star disruption

GRB–GW Search Results





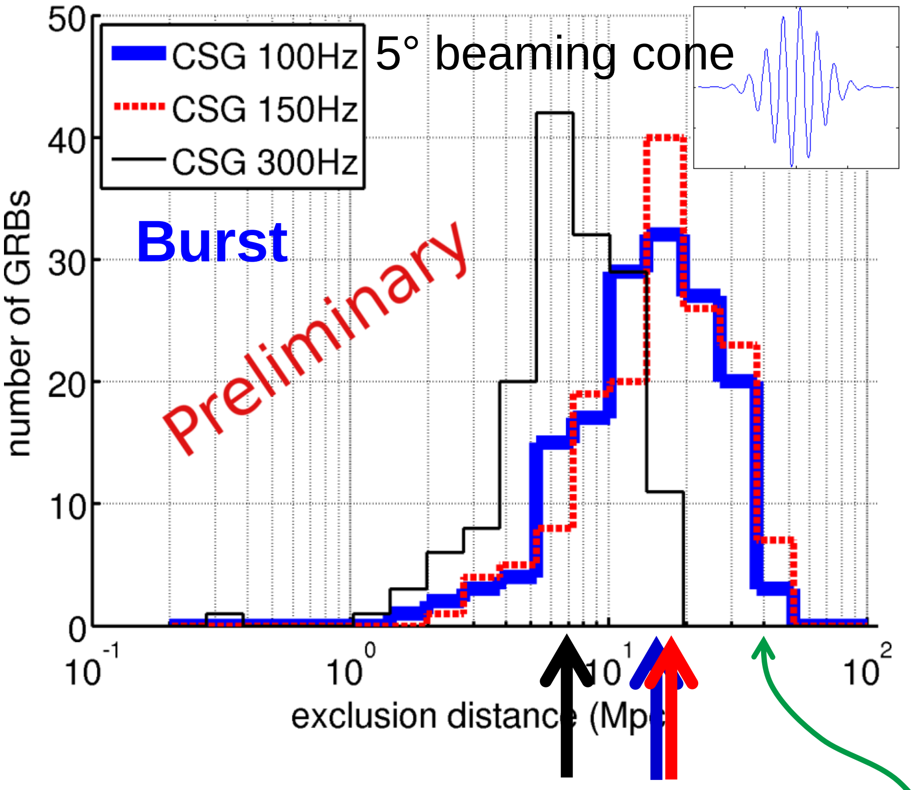
No individual GRB stands out compared to the background

No subset of the most significant GRBs stands out either

“Weighted binomial test” statistic is consistent with uniform distribution

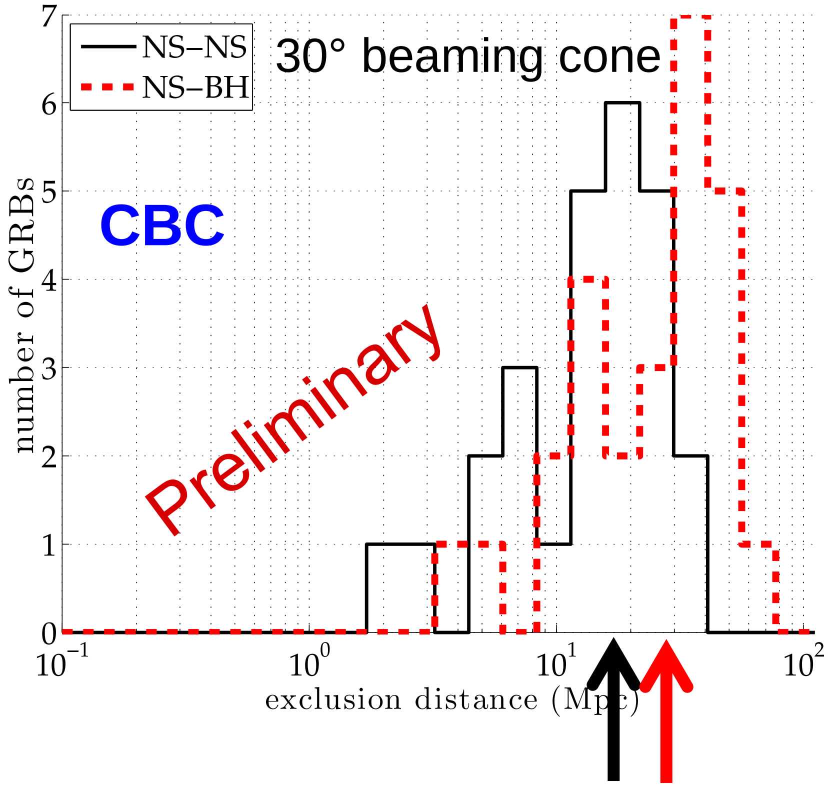
GRB Progenitor Exclusion Distances

Assuming sine-Gaussian waveform with optimistic but possible $E_{GW} = 0.01\ M_{\odot}c^2$



Median distances: 7, 15,17 Mpc

Assuming coalescence of NS-NS or NS-BH binary

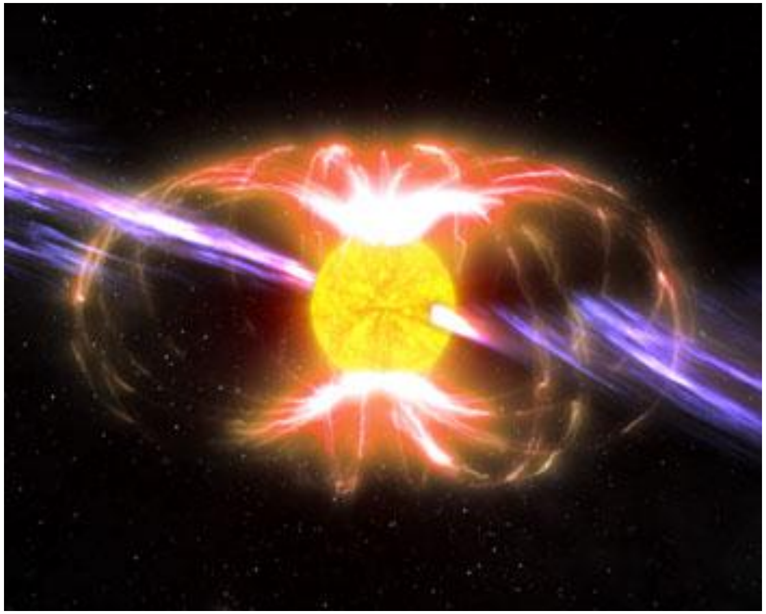


Median distances: 17, 29 Mpc

Distance to GRB 980425 / SN 1998bw

e.g. Kulkarni et al., Nature 395, 663

Magnetar Flares



Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are believed to be magnetars

- Neutron stars with magnetic field ~10^{15} G interacting with crust

Occasionally emit flares of soft gamma rays

- Ordinary flares E_{EM} ~ 10^{42} erg
- Some SGRs have produced a ***giant flare*** with energy ~10^{46} erg

Thought to be associated with cracking of the crust ("starquake") or magnetic reconnection

- Quasiperiodic oscillations seen in X-ray emission after giant flares
- May excite non-radial oscillation modes that couple to GW emission

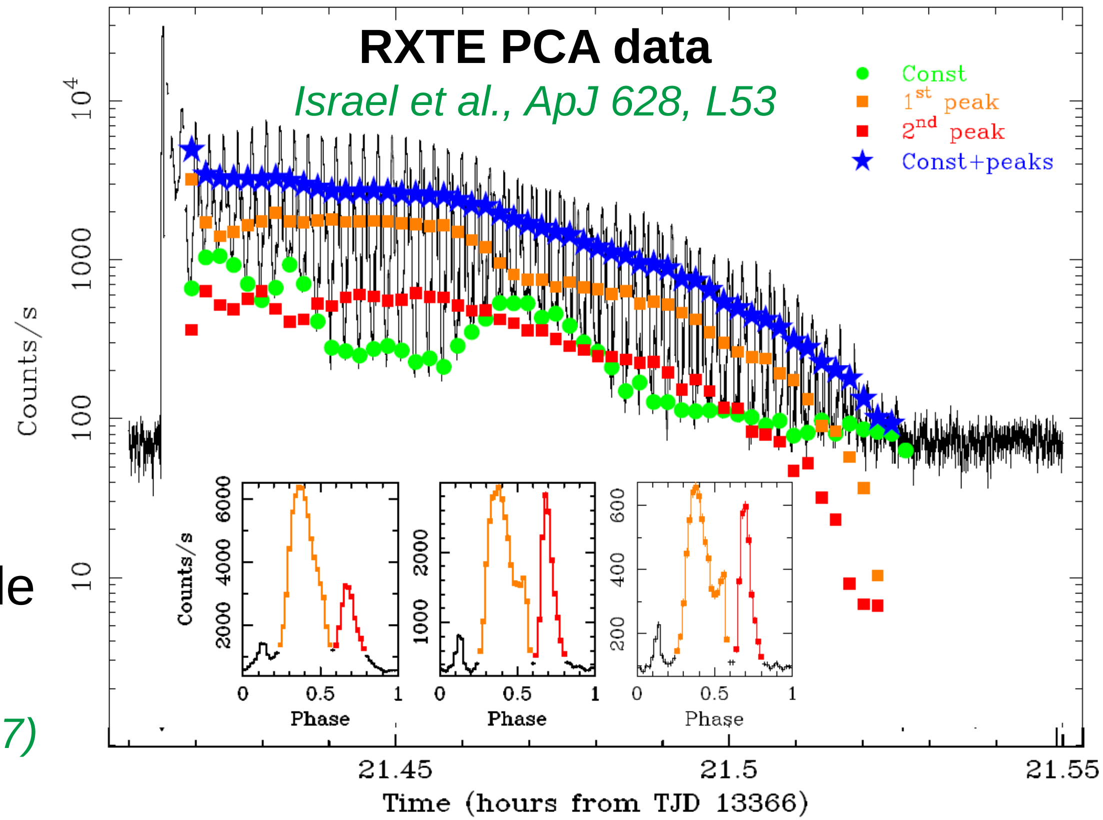
Searches for GW Signals from Magnetars

Long-lived quasiperiodic GWs after giant flare ?

December 2004 giant flare of SGR 1806–20

Searched for GW signals with same frequencies and time spans as X-ray QPOs detected by RXTE and RHESSI:

92.5, 150, 626, 1837 Hz



GW energy limits comparable to total EM energy emission

Abbott et al., PRD 76, 062003 (2007)

Searches for GW Signals from Magnetars

GW bursts at times of magnetar flares ?

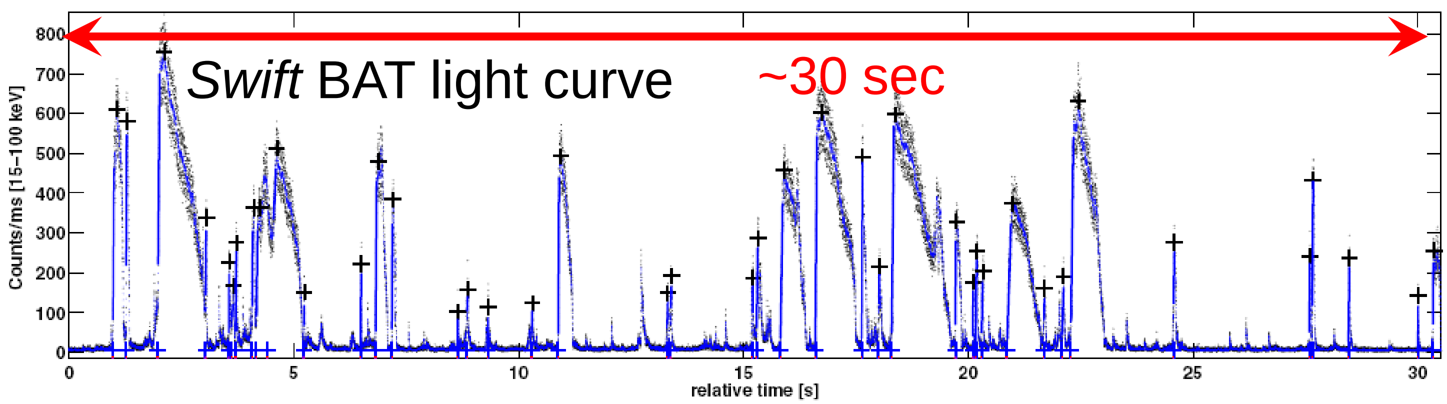
2004 giant flare plus other flares from SGR 1806–20 and 5 others

Excess-power search for neutron star *f*-modes ringing down (~1.5–3 kHz) as well as for arbitrary lower-frequency bursts

For certain assumed waveforms, GW energy limits are as low as few × 10^{45} erg, comparable to EM energy emitted in giant flares

Abbott et al., PRL 101, 211102 ; Abadie et al., ApJ 734, L35

Also a “stacked” search for repeated emission from SGR 1900+14 “storm” on March 29, 2006 – tighter GW energy upper limits under this model

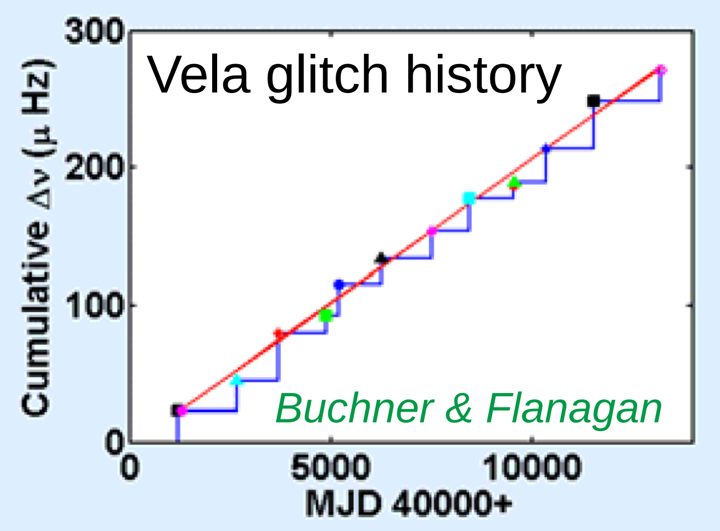


Abbott et al., ApJ 701, L68

Other Externally Triggered Searches

Search for GWs associated with pulsar timing glitches

First published result:
Aug. 2006 glitch of Vela pulsar
with $\Delta\nu/\nu = 2.6 \times 10^{-6}$
(measured by S. Buchner and
C. Flanagan of HartRAO)



Searched for "ringdown" GW signal
at *f*-mode frequencies, 1–3 kHz,
with decay timescales 50–500 ms

Placed (weak) limits on GW energy emission

Abadie et al, PRD 83, 042001 (2011)

Supernova triggered searches

We haven't published any yet, but are working on it

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Search for GWs from the Crab Pulsar

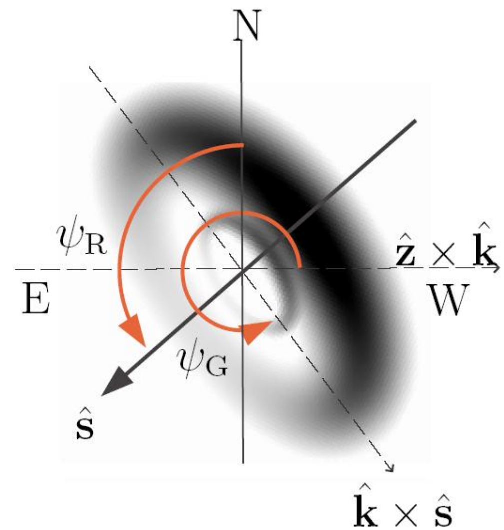
The Crab pulsar spin rate is slowing down – do GWs contribute?

Search for a continuous-wave (CW) signal at twice the spin frequency, demodulating detector motion

X-ray observations tell us the orientation of the spin axis

Chandra image

Model



No GW signal detected *Abbott et al., ApJ 713, 671 (2010)*

Upper limit on GW strain amplitude: $h_0 < 2 \times 10^{-25}$

Implies GW emission accounts for $\leq 2\%$ of total spin-down power

Other Known Pulsars in LIGO/Virgo Band

Fully coherent analysis at twice the spin frequency

Relies on having good radio (or X-ray) timing, ideally during the period of GW data collection

Vela – using Virgo data
Abadie et al., ApJ 737, 93

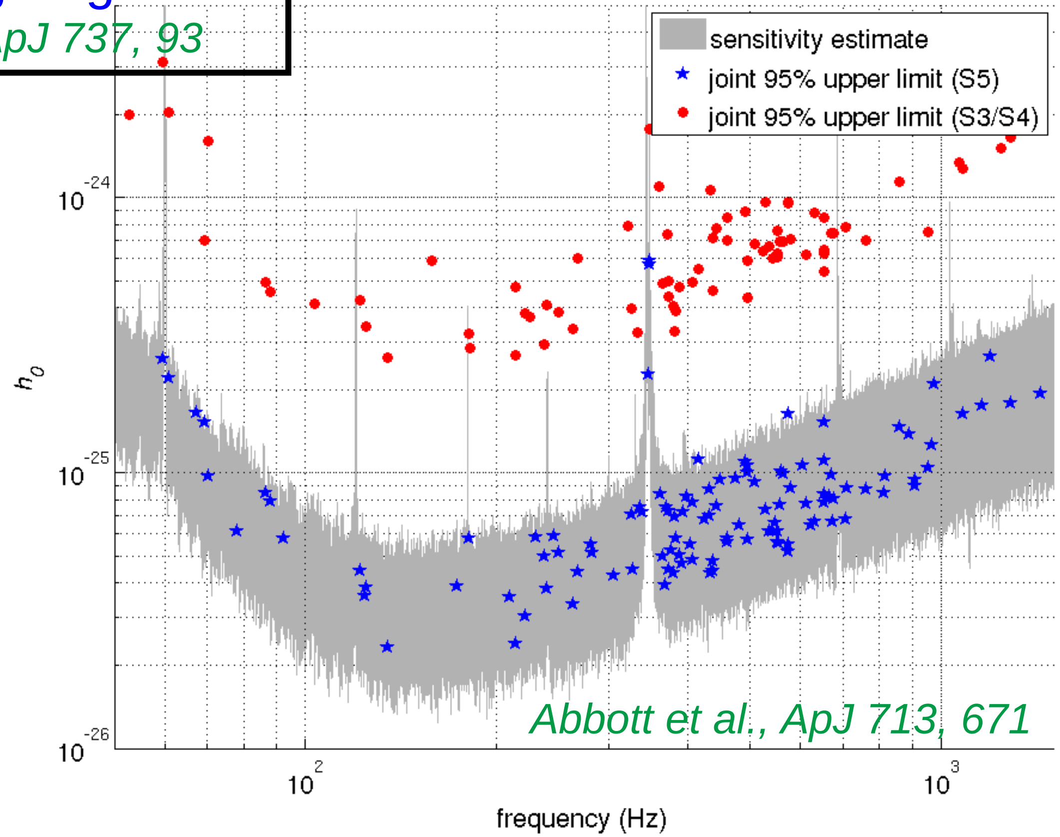
Lowest upper limit on strain:

$$h_0 < 2.3 \times 10^{-26}$$

Lowest upper limit on ellipticity:

$$\varepsilon < 7 \times 10^{-8}$$

Reached spin-down limit for Crab, Vela, and J0537–6910



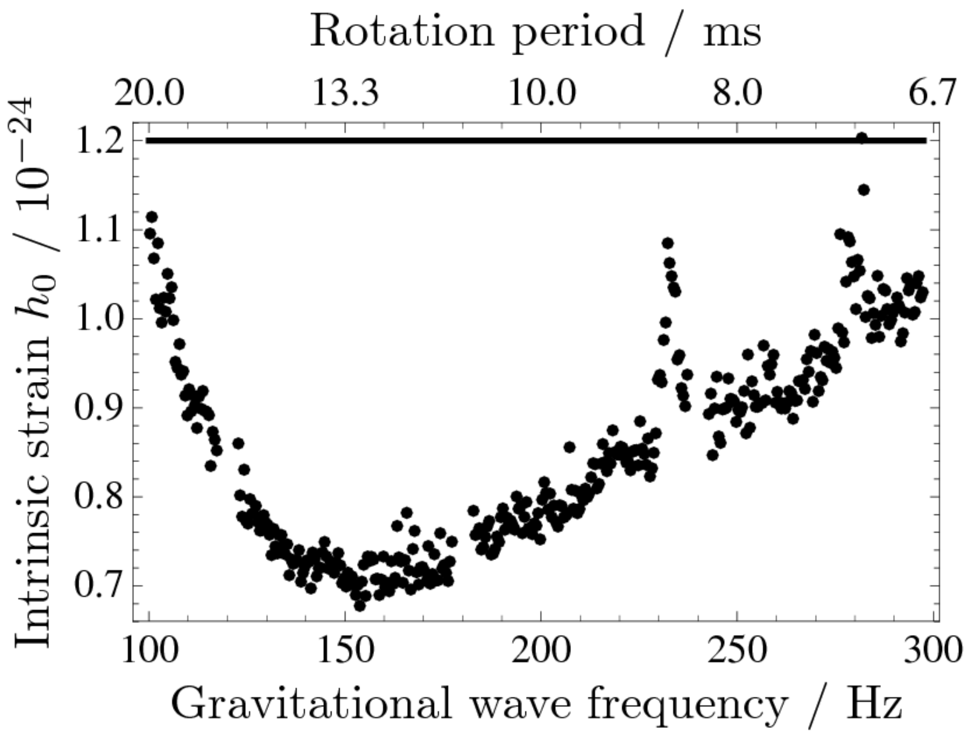
Abbott et al., ApJ 713, 671

Targeting a Non-Pulsing Neutron Star

Search for periodic GW signal from the remnant in Cas A

Spin frequency is unknown, and young age requires considering second derivative of frequency

Fully coherent search using 12 days of data



indirect upper limit based on age and distance

Set upper limits below indirect UL over the range 100–300 Hz

Abbott et al., ApJ 722, 1504 (2010)

Other Loosely Guided CW Searches

Known pulsars

Allow f_{GW} to deviate slightly from $2f_{spin}$

Done so far for the Crab pulsar, with up to 10^{-4} relative frequency shift

Abbott et al., ApJ 683, L45 (2008)

Search for combined f_{spin} and $2f_{spin}$ signals

Targeting non-pulsars

LMXBs

Published search for GWs from Sco X-1 in two 20-Hz frequency bands using 6 hours of LIGO S2 data *Abbott et al., PRD 76, 082001 (2007)*

Other LMXB searches in progress

Supernova remnants

Globular clusters

The Galactic center

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Escalate Already-Observed EM Events?

We haven't done that yet.

Closest thing: GW detector network status at times of GRBs

https://ldas-jobs.ligo.caltech.edu/~xpipeline/S6/grb/online/search/ligovirgo_grbstatus_S6.html

Satellite	GCN Reference	GRB Date	Trigger Time		Coordinates		IFO in Science	Data Availability	Status Update Time (UTC)
			UT	GPS	R.A. (deg)	Dec (deg)			
Fermi	N 309317433	101021	01:30:31.66	971659846.66	359.050	49.100	--	NOIFO	Oct 21 2010 05:26:37
Fermi	N 309312807	101021	00:13:25.36	971655220.36	5.670	-21.300	--	NOIFO	Oct 21 2010 04:54:23
Swift	N 436737	101020	23:40:41.70	971653256.70	189.566	23.161	--	NOIFO	Oct 20 2010 23:56:02
Fermi	N 309019891	101017	14:51:29.48	971362304.48	31.600	-32.610	V1	ONEIFO	Oct 17 2010 15:14:29
Swift	N 436429	101017	10:32:47.41	971346782.41	291.378	-35.141	H1V1	NETWORK	Oct 17 2010 10:49:30
Fermi	N 308901018	101016	05:50:16.07	971243431.07	134.380	-4.820	L1V1	NETWORK	Oct 16 2010 06:14:25
Fermi	N 308841844	101015	13:24:02.67	971184257.67	88.420	39.460	H1L1	NETWORK	Oct 15 2010 13:44:22
Fermi	N 308722314	101014	04:11:52.62	971064727.62	25.783	-50.567	--	NOIFO	Oct 14 2010 04:34:20
Fermi	N 308656364	101013	09:52:42.87	970998777.87	276.910	-45.420	H1L1V1	NETWORK	Oct 13 2010 10:14:17
Swift	N 436094	101011	16:58:35.33	970851530.33	48.298	-65.986	H1	ONEIFO	Oct 11 2010 17:13:51
Fermi	N 308378028	101010	04:33:46.83	970720441.83	70.250	21.733	L1V1	NETWORK	Oct 10 2010 04:58:34
Swift	N 435903	101008	16:43:15.21	970591410.21	328.891	37.062	V1	ONEIFO	Oct 08 2010 17:02:43
Fermi	N 307880031	101004	10:13:49.46	970222444.46	237.183	-46.267	H1L1	NETWORK	Oct 04 2010 10:35:58
Swift	N 435520	101003	09:18:01.76	970132696.76	300.937	32.386	H1L1V1	NETWORK	Oct 03 2010 09:35:53
Fermi	N 307777870	101003	05:51:08.01	970120283.01	183.370	3.930	H1L1V1	NETWORK	Oct 03 2010 06:15:52
Fermi	N 307694488	101002	06:41:26.95	970036901.95	330.950	-41.350	H1V1	NETWORK	Oct 02 2010 07:05:42
Fermi	N 307490387	100929	21:59:45.82	969832800.82	188.710	-12.010	H1V1	NETWORK	Sep 29 2010 22:20:29
Fermi	N 307438386	100929	07:33:04.05	969780799.05	289.850	31.020	L1V1	NETWORK	Sep 29 2010 07:55:25

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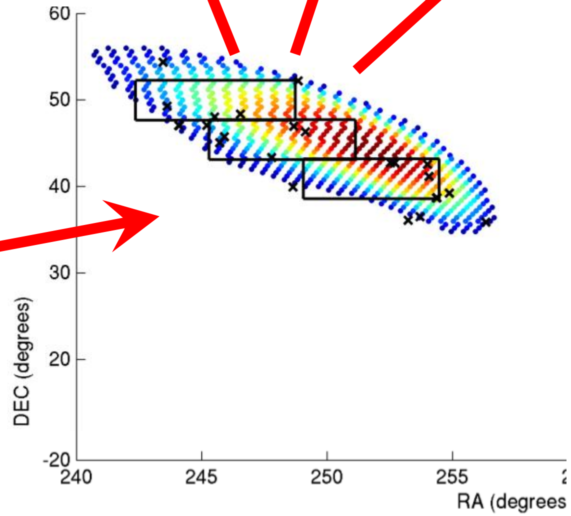
EM Follow-ups: The Basic Idea

...

Analyze GW data, select candidates



First Take on Observing Strategy Inputs

Time scales

Supernova: rise after ~1 day or later, last for weeks

NS binary "kilonova" peaking after ~1 day *[Metzger et al., MNRAS 406, 2650]*

GRB (or orphan) afterglow: roughly power-law fading

Prompt optical emission: seen as early as 10–20 s after *some* GRBs *[e.g. Klotz et al., AJ 137, 4100 ; Racusin et al., Nature 455, 183]*

⇒ Analyze GW data and get first image ASAP, plus later images

Expected brightness

Nearby ⇒ possibly quite bright ⇒ Small-aperture telescopes are OK

NS-NS kilonova model: peak magnitude V~18 at 50 Mpc

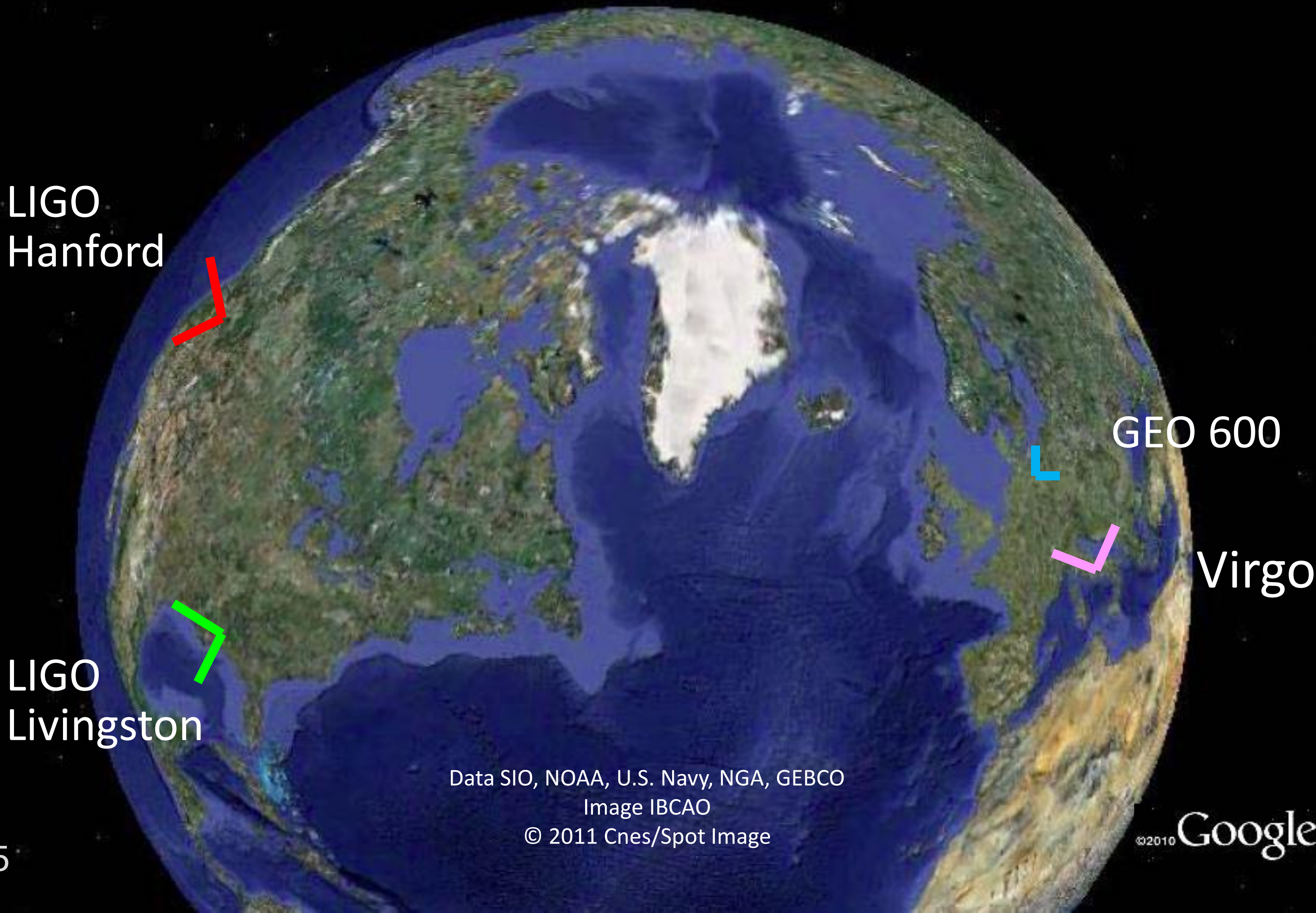
GW position reconstruction precision

Many square degrees ⇒ Favors wide-field telescopes

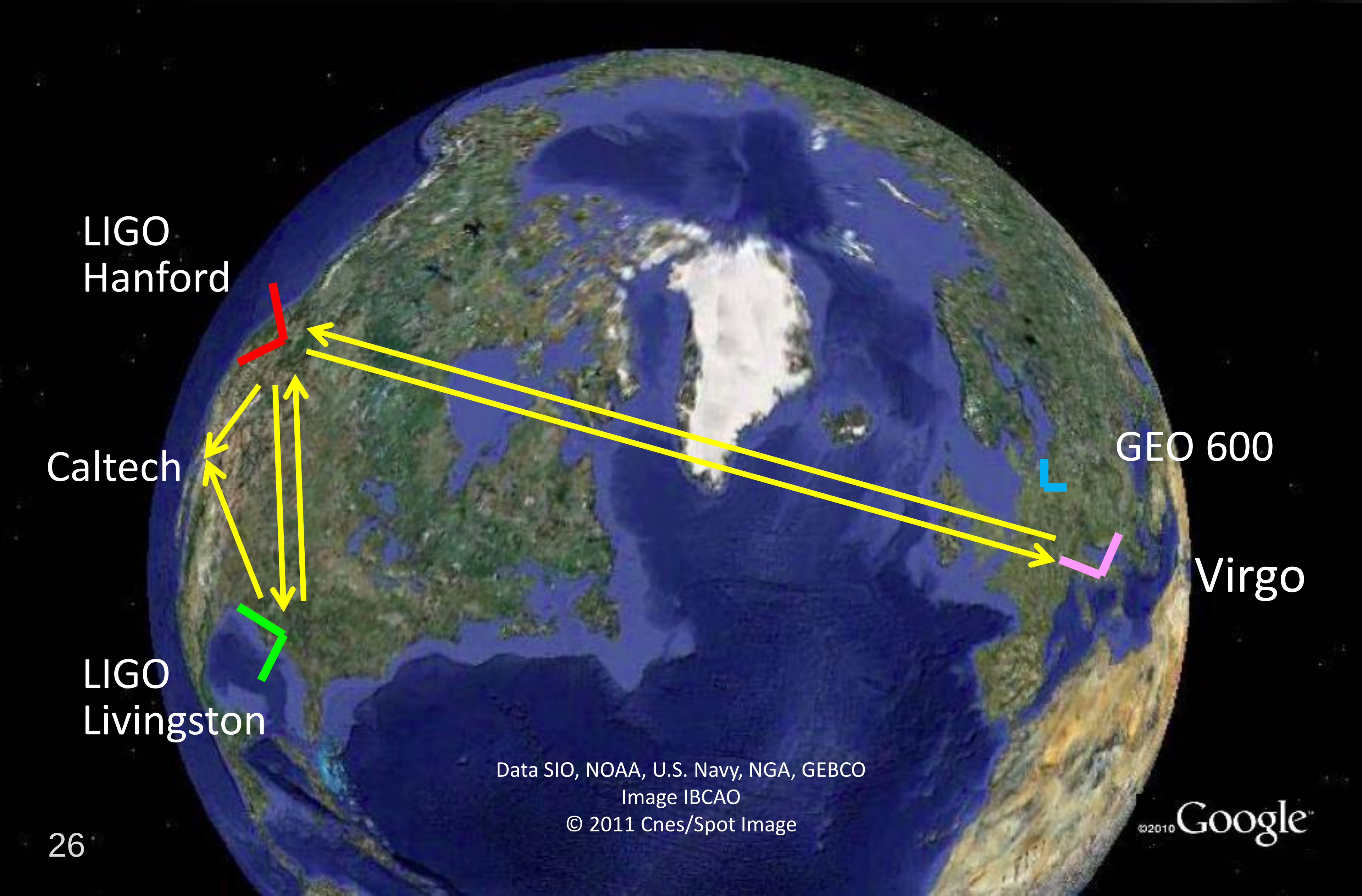
Trigger threshold

Set relatively low, based on what partners are willing to follow up

First Implementation: 2009–2010



Low-Latency Calibration and Data Transfer



Online Data Analysis

Burst Search

Two search algorithms: *Coherent WaveBurst* and *Omega Pipeline*

Sensitive to essentially any signal with duration up to ~1 s

Fully coherent analysis considering all possible sky positions

CBC Inspiral Search

Search algorithm: *MBTA* (multi-band template analysis)

Consider binaries with at least one neutron star

Coincidence analysis, then use relative arrival times of triggers to triangulate sky position

Abadie et al., A&A in press, arXiv:1112.6005

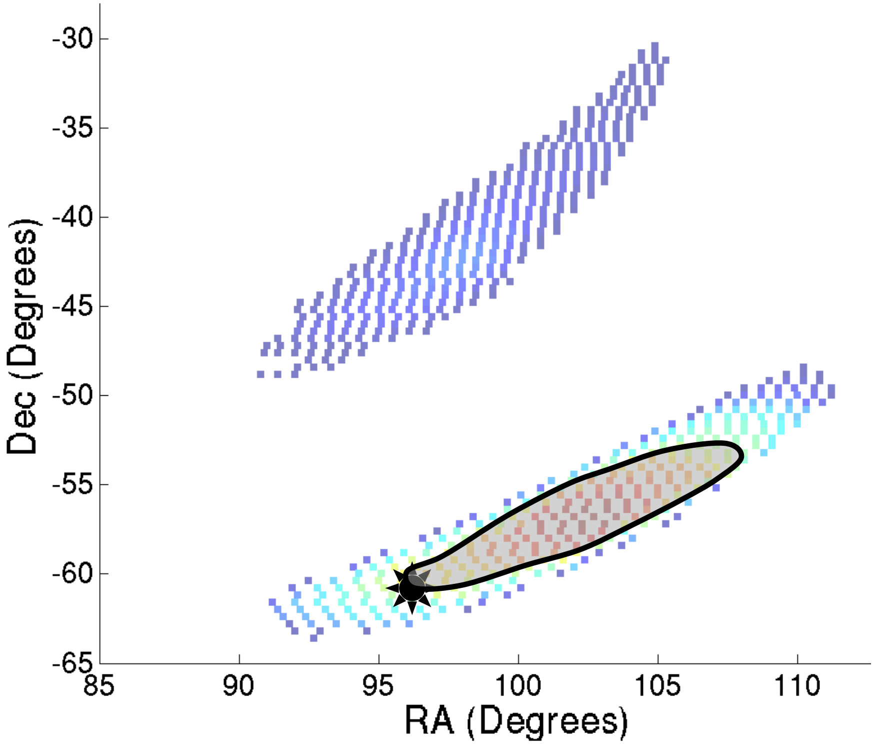
Each search pipeline calculates a detection statistic

- Background estimated using time-shifted data

Search output: "triggers" with event time, significance (false alarm rate), sky probability map

How Well Can We Reconstruct Position?

Sample sky map:

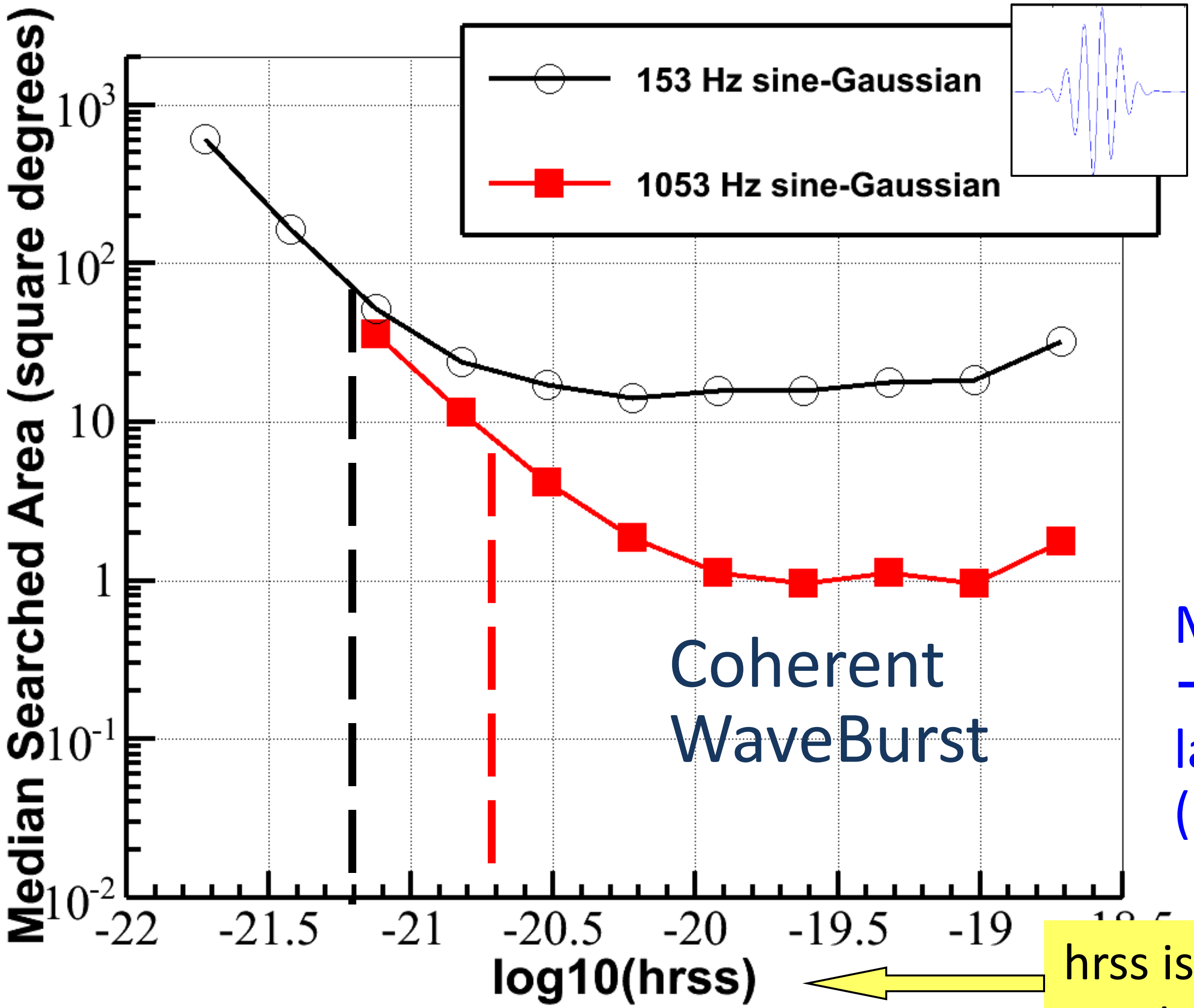


- Likelihood calculated for each trial position pixel
- Often get multiple, irregularly shaped regions

- Check sky map relative to **injected position**

- “Searched area” figure of merit is defined as the area of the sky map ranked higher than the true location
- Run the simulation and search algorithm many times

Position Reconstruction Example



Dashed lines indicate hrss for 50% detection efficiency in all-sky burst search

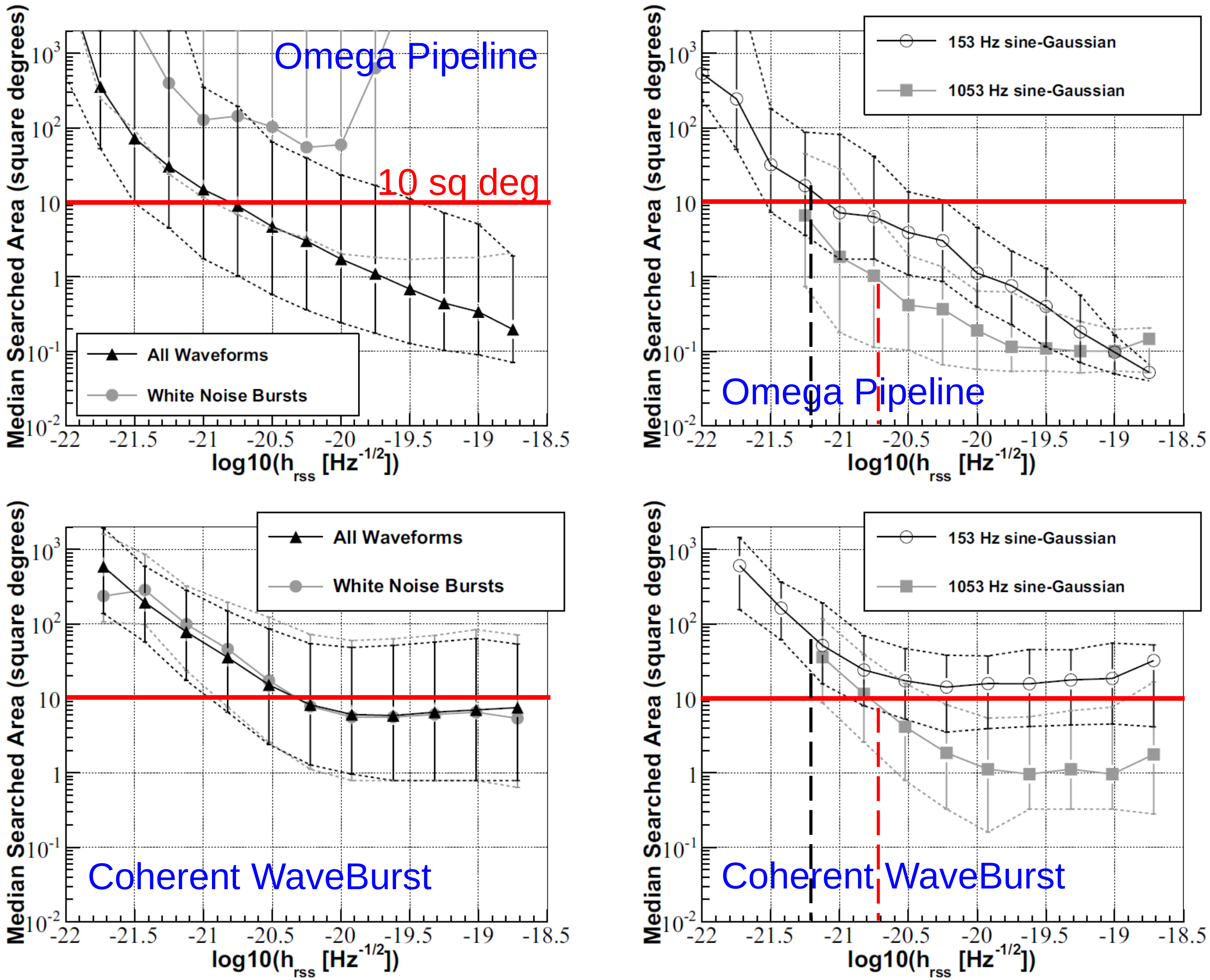
Abadie et al, PRD 81, 102001; arXiv:1202.2788

Many square degrees → Suggests using large field-of-view (FOV) instruments

hrss is a measure of signal amplitude at Earth

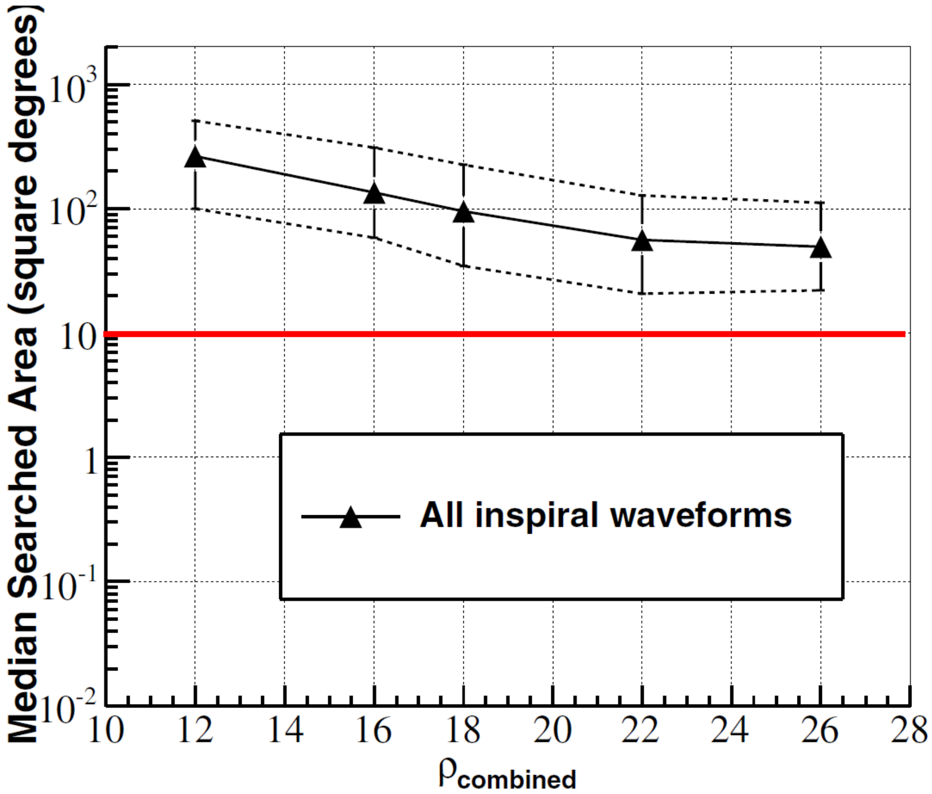
LSC+Virgo+others, A&A 539, A124 (2012)

Searched Area Dependence on Signal – Bursts



Searched Area Dependence on Signal – Inspiral

Using time-of-flight triangulation from coincident MBTA triggers



Full coherent parameter estimation can give better positions

But takes a long time to compute

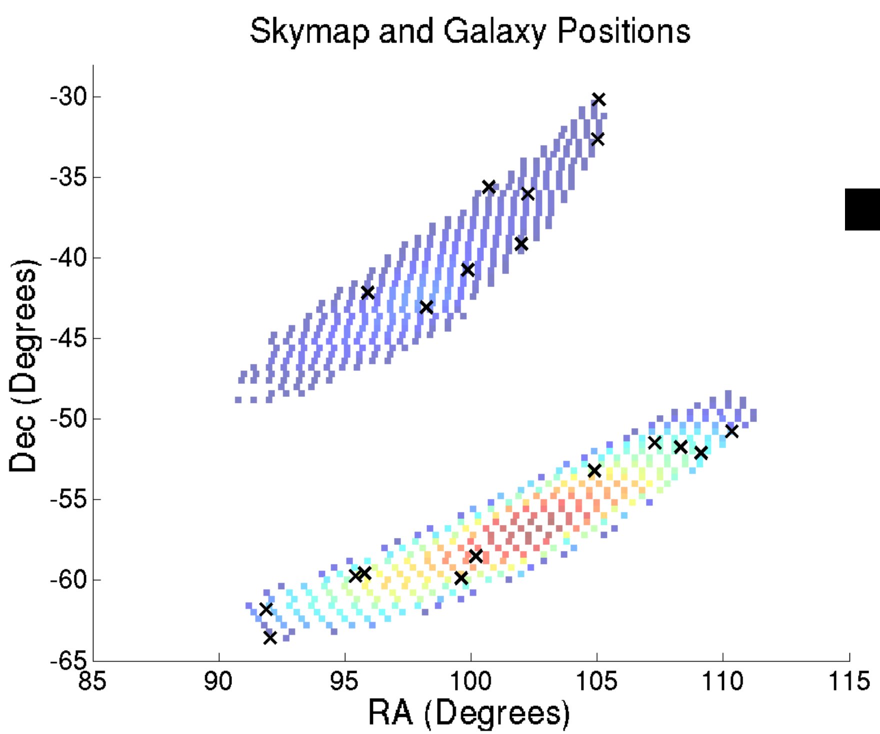
LUMIN Galaxy Targeting

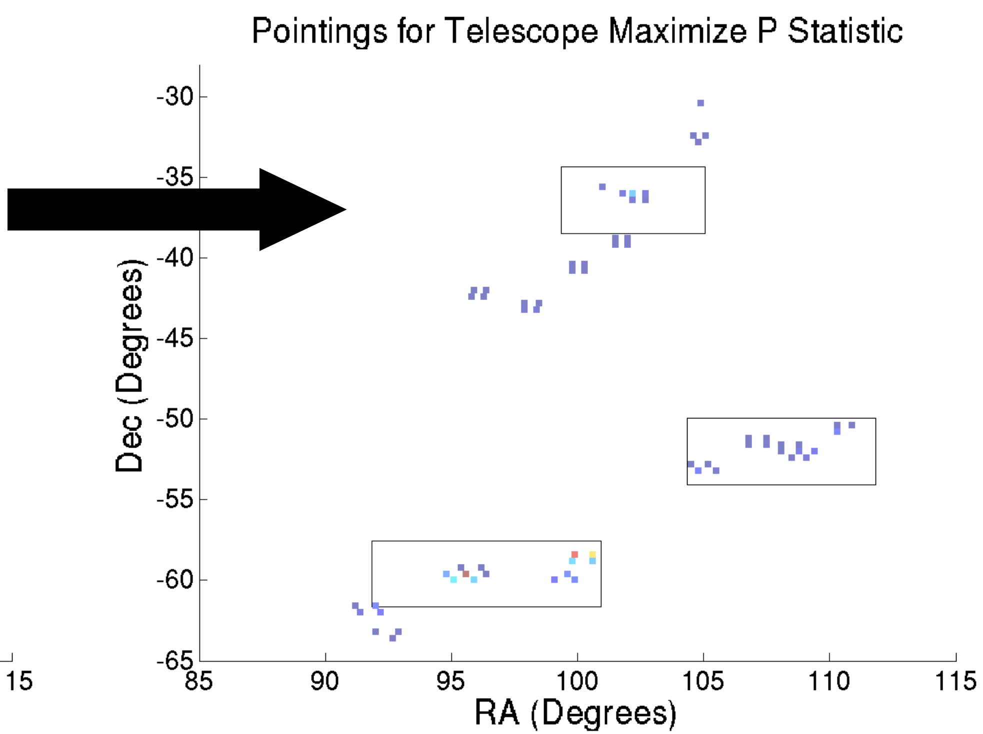
Use positions of known galaxies within 50 Mpc

White et al., CQG 28, 085016

Weight by blue light luminosity, and inversely by distance

MBTA: only consider galaxies closer than measured effective distance for the trigger





Event Candidate Selection Issues

Significance (false alarm rate) of the trigger

- Evaluated using recent background distribution

Degree of localization

- More costly to cover large sky area, especially with small FOV scope

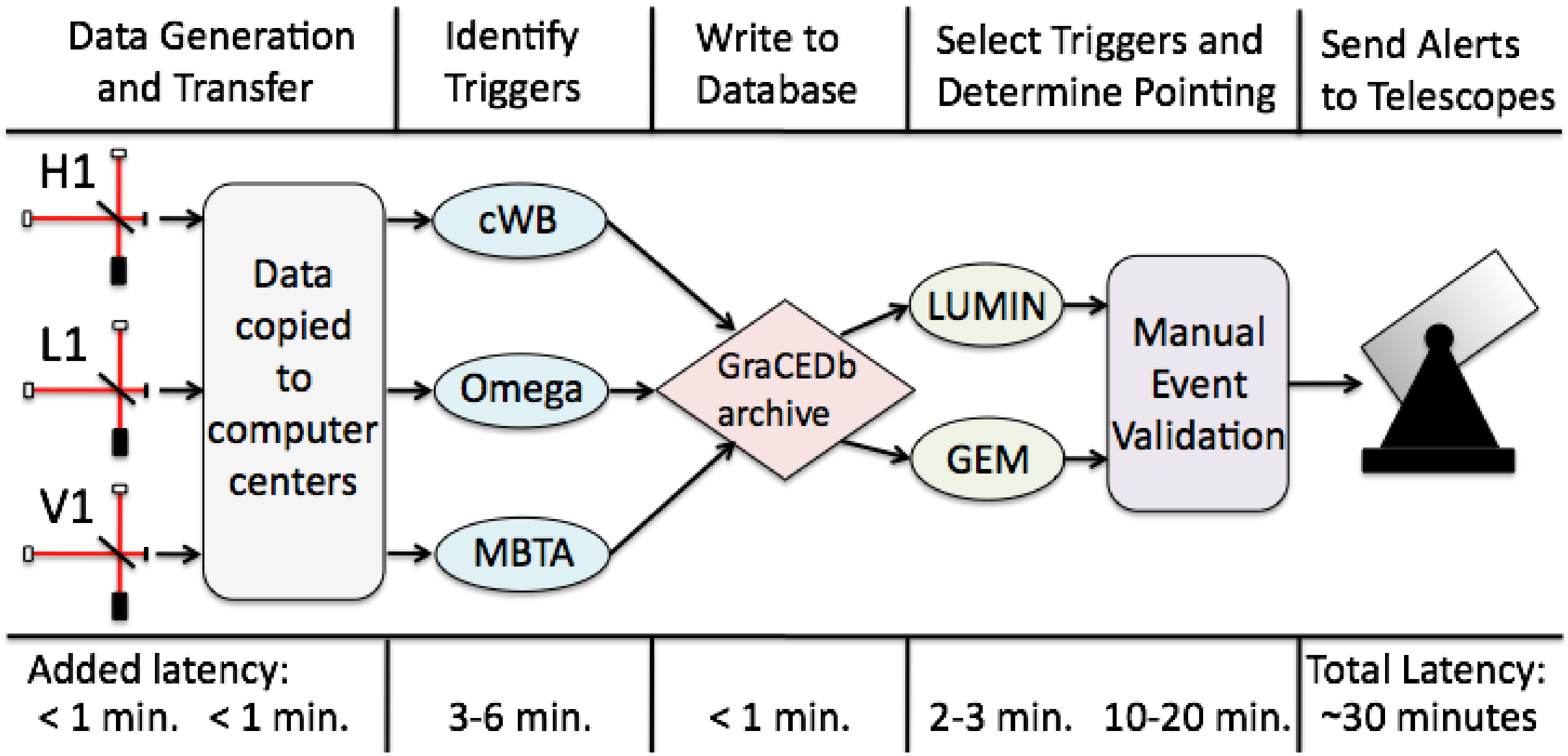
Data quality checks

- Some basic things evaluated online, checked automatically

Manual event validation

- Checklist of additional things to make sure nothing was obviously wrong with the data
- Done by scientific monitors and operators in control rooms, assisted by on-call expert

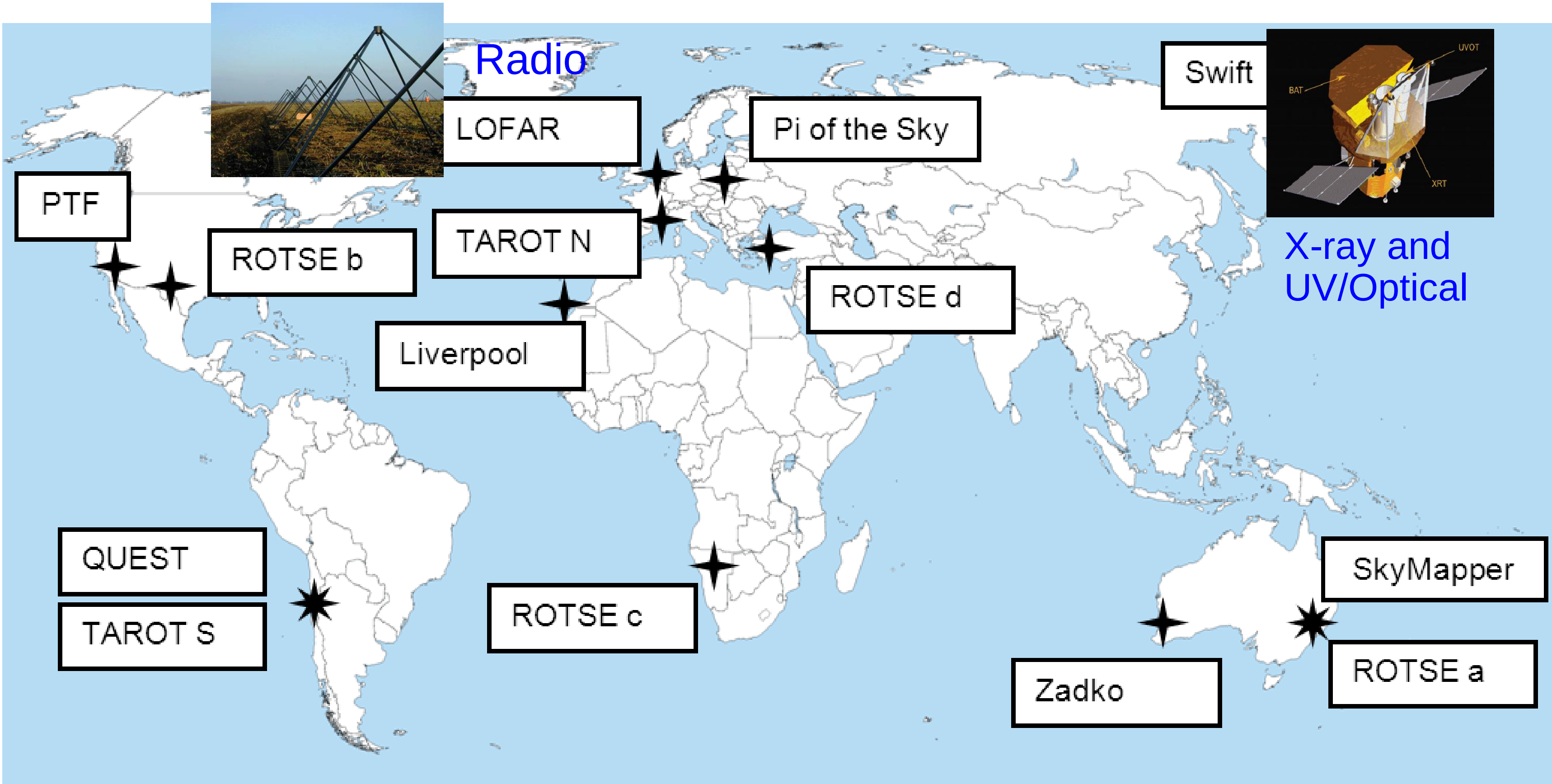
First Implementation: 2009–2010



LUMIN and GEM selected significant event candidates, alerted humans (on call 24/7 in shifts) to complete manual validation, chose target coordinates and communicated with telescopes

LSC+Virgo+others, A&A 539, A124 (2012)

Observing Partners During 2009–2010



Mostly (but not all) robotic wide-field optical telescopes

Many of them used for following up GRBs, surveying for supernovae and other optical transients

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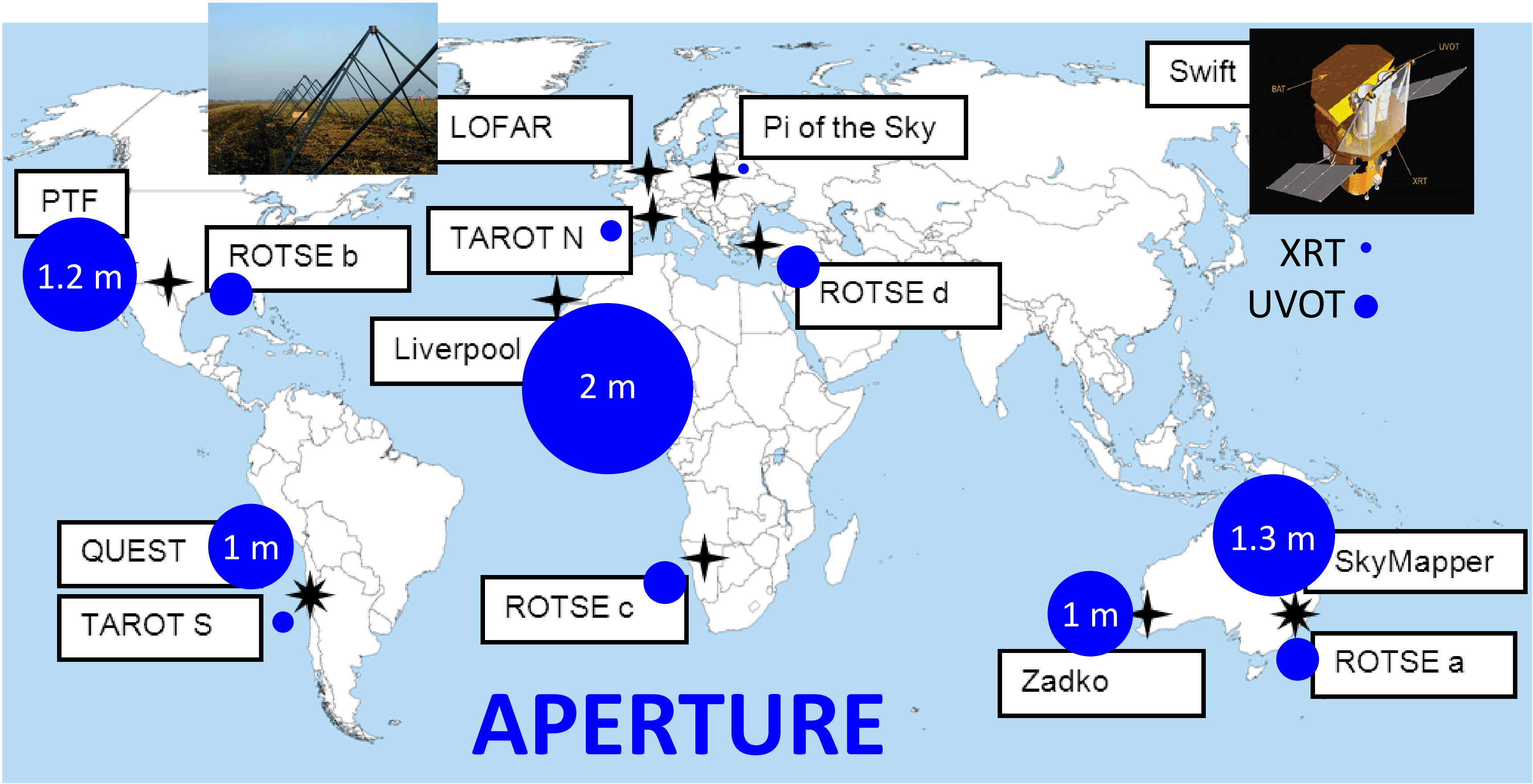

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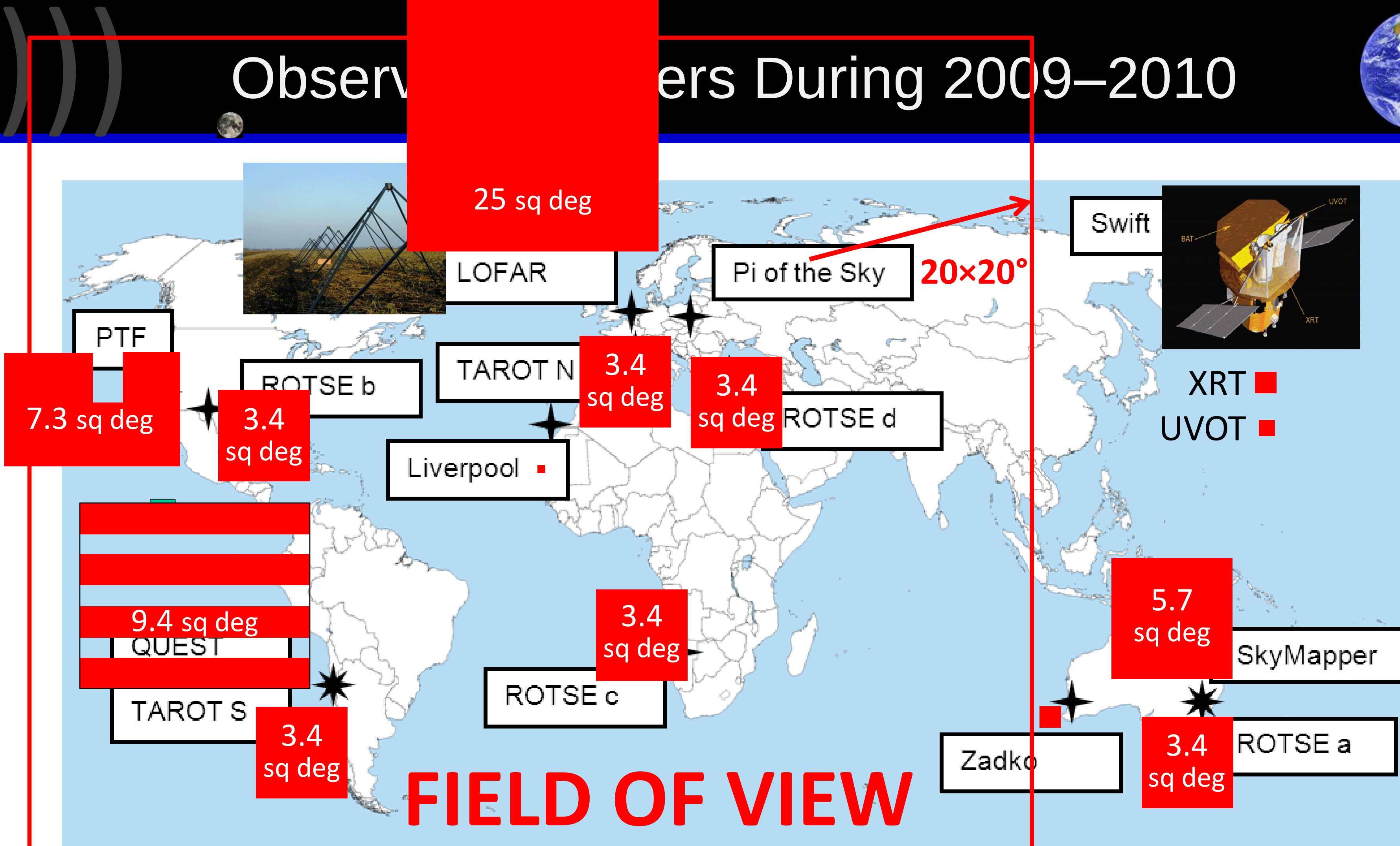
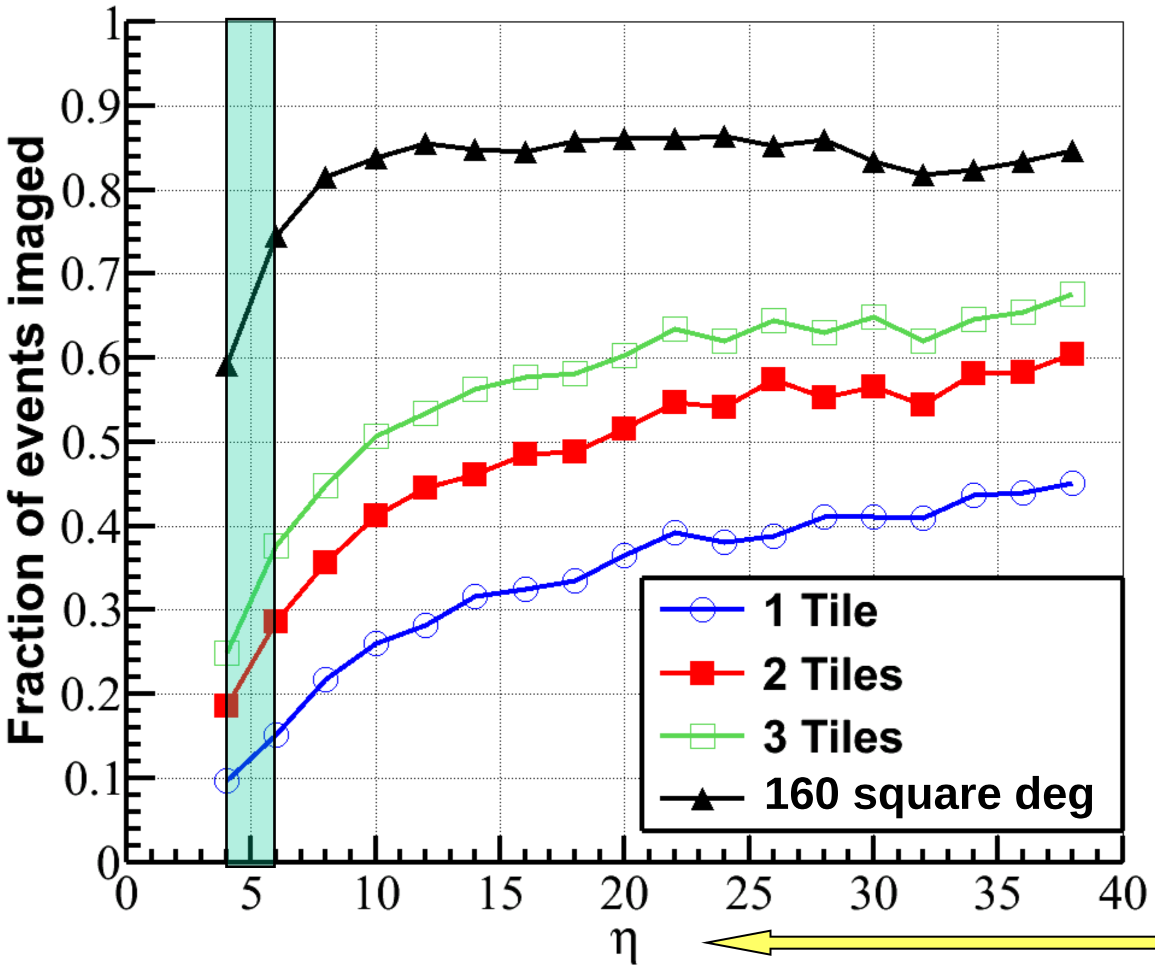


Mostly (but not all) robotic wide-field optical telescopes

Many of them used for following up GRBs, surveying for supernovae and other optical transients

Targeting Success Example

Coherent WaveBurst, ROTSE/TAROT FOV



Shaded box shows range of nominal detection thresholds in S5/VSR1 search

η is "coherent SNR" measured by cWB; roughly proportional to network SNR

EM Follow-up Operations

"Live" for two running periods

S6/VSR2: 17 Dec 2009 to 8 Jan 2010

S6/VSR3: 2 Sept to 20 Oct 2010

Target trigger rates

S6/VSR2: 1 per day of 3-site science mode

S6/VSR3: 0.25 per day of 3-site science mode

Tighter requirements for Swift, PTF

Sent alerts to scopes, which took images when possible

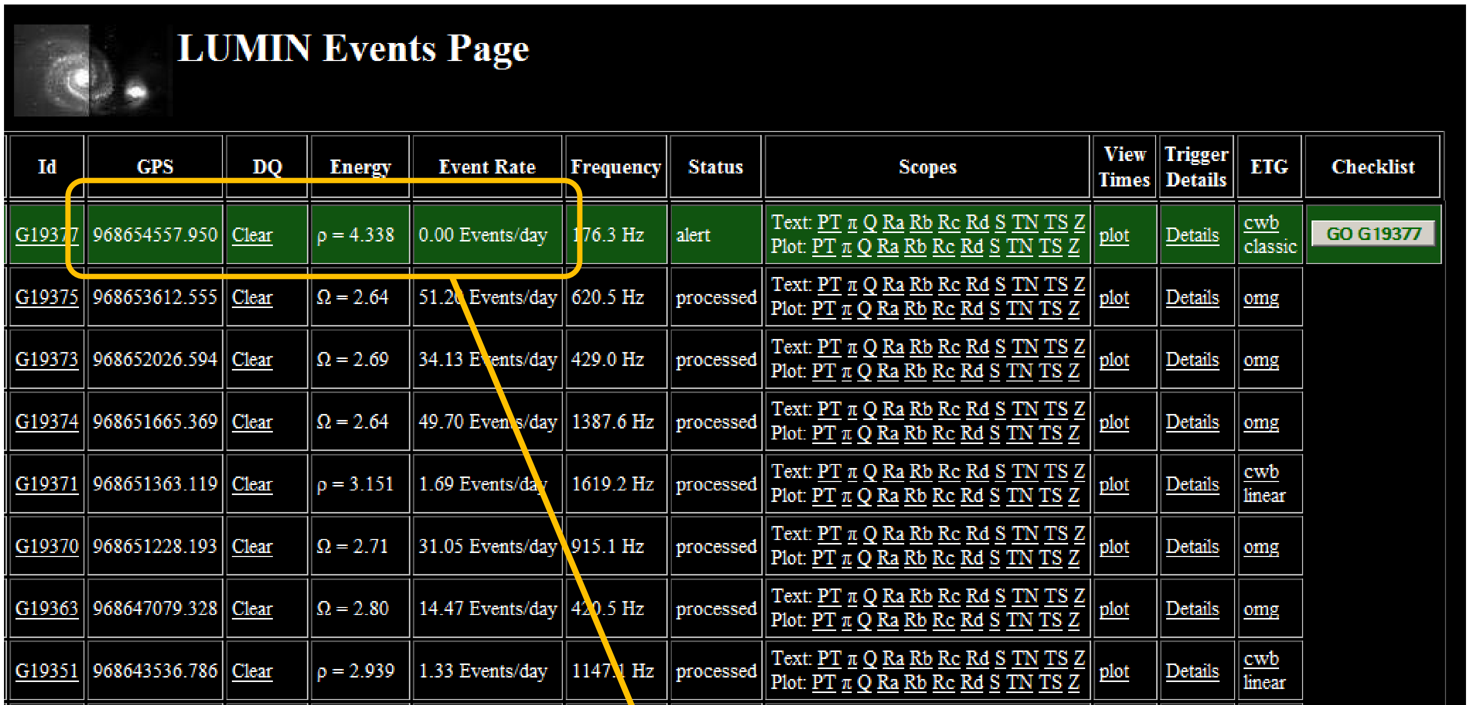
Sent specific coordinates chosen for that scope's FOV

9 event candidates were followed up by at least one scope

Generally observed the targets as soon as possible (given constraints of daylight, weather, etc.) and again on one or more of later nights

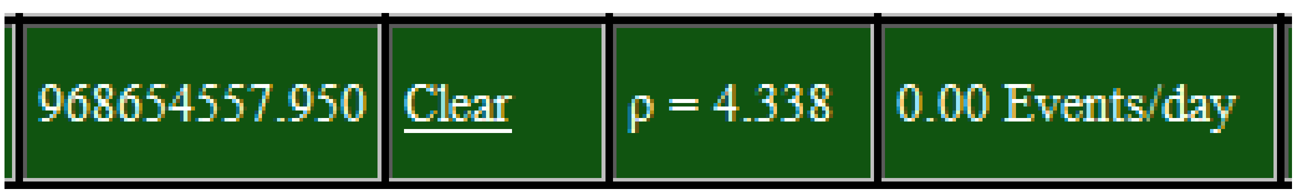
- Details varied from scope to scope

2:50 a.m. EDT: My cell phone beeps — it’s a LUMIN alert



LUMIN Events Page

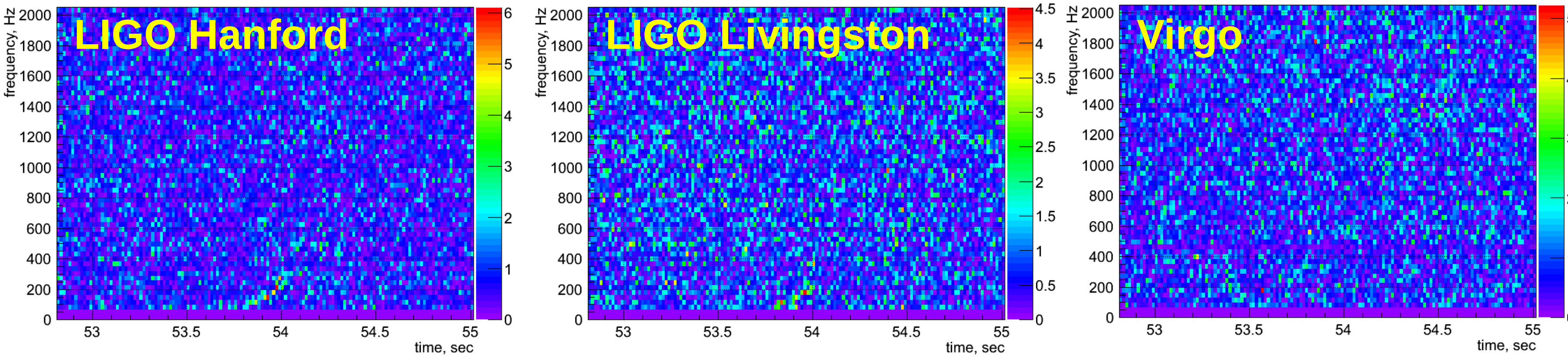
Id	GPS	DQ	Energy	Event Rate	Frequency	Status	Scopes	View Times	Trigger Details	ETG	Checklist
G19377	968654557.950	Clear	ρ = 4.338	0.00 Events/day	176.3 Hz	alert	Text: PT π Q Ra Rb Rc Rd S TN TS Z Plot: PT π Q Ra Rb Rc Rd S TN TS Z	plot	Details	cwb classic	GO G19377
G19375	968653612.555	Clear	Ω = 2.64	51.20 Events/day	620.5 Hz	processed	Text: PT π Q Ra Rb Rc Rd S TN TS Z Plot: PT π Q Ra Rb Rc Rd S TN TS Z	plot	Details	omg	
G19373	968652026.594	Clear	Ω = 2.69	34.13 Events/day	429.0 Hz	processed	Text: PT π Q Ra Rb Rc Rd S TN TS Z Plot: PT π Q Ra Rb Rc Rd S TN TS Z	plot	Details	omg	
G19374	968651665.369	Clear	Ω = 2.64	49.70 Events/day	1387.6 Hz	processed	Text: PT π Q Ra Rb Rc Rd S TN TS Z Plot: PT π Q Ra Rb Rc Rd S TN TS Z	plot	Details	omg	
G19371	968651363.119	Clear	ρ = 3.151	1.69 Events/day	1619.2 Hz	processed	Text: PT π Q Ra Rb Rc Rd S TN TS Z Plot: PT π Q Ra Rb Rc Rd S TN TS Z	plot	Details	cwb linear	
G19370	968651228.193	Clear	Ω = 2.71	31.05 Events/day	915.1 Hz	processed	Text: PT π Q Ra Rb Rc Rd S TN TS Z Plot: PT π Q Ra Rb Rc Rd S TN TS Z	plot	Details	omg	
G19363	968647079.328	Clear	Ω = 2.80	14.47 Events/day	420.5 Hz	processed	Text: PT π Q Ra Rb Rc Rd S TN TS Z Plot: PT π Q Ra Rb Rc Rd S TN TS Z	plot	Details	omg	
G19351	968643536.786	Clear	ρ = 2.939	1.33 Events/day	1147.1 Hz	processed	Text: PT π Q Ra Rb Rc Rd S TN TS Z Plot: PT π Q Ra Rb Rc Rd S TN TS Z	plot	Details	cwb linear	



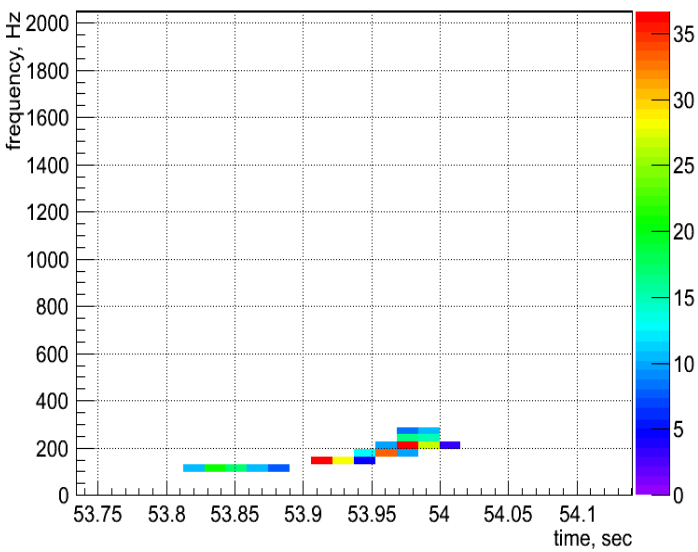
968654557.950	Clear	ρ = 4.338	0.00 Events/day

What Does the Signal Look Like?

Coherent WaveBurst time-frequency pixel maps:



Likelihood detection statistic:

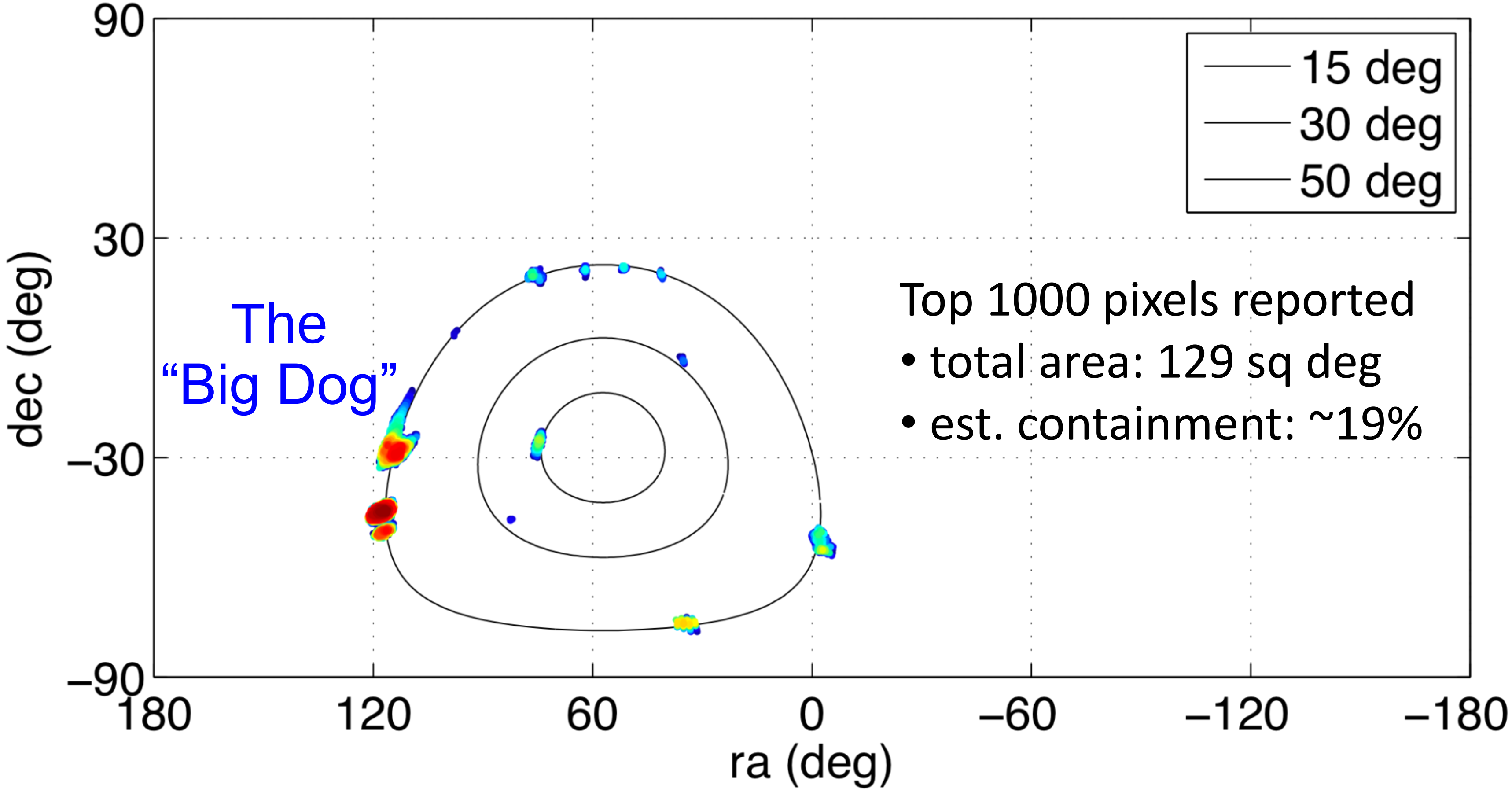


What could it be?

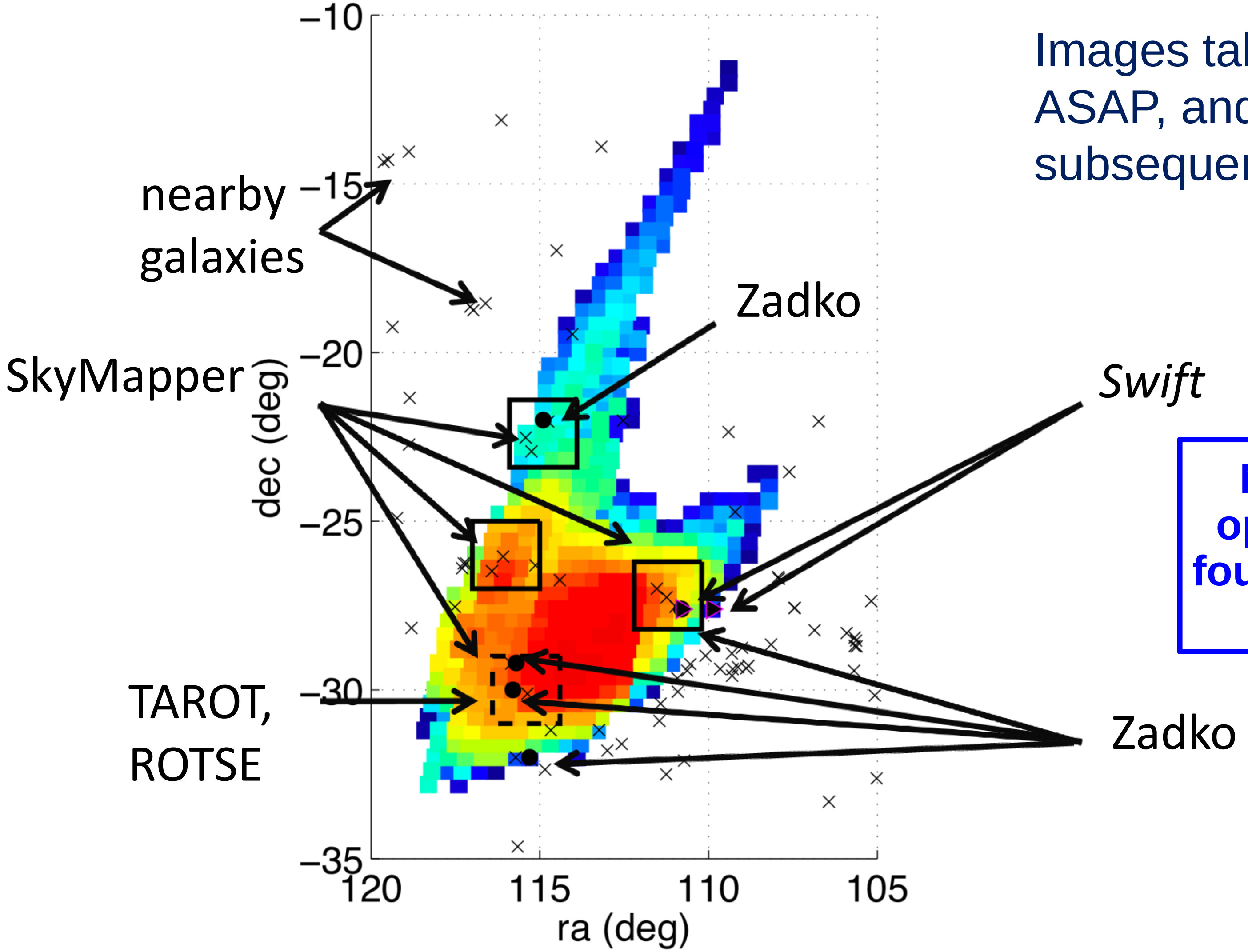
- A binary black hole inspiral / merger
- A noise fluctuation
- A “blind injection” (simulated signal injected into the interferometer)

Where is it Coming From?

Coherent WaveBurst probability sky map:



Regions Imaged by Telescopes

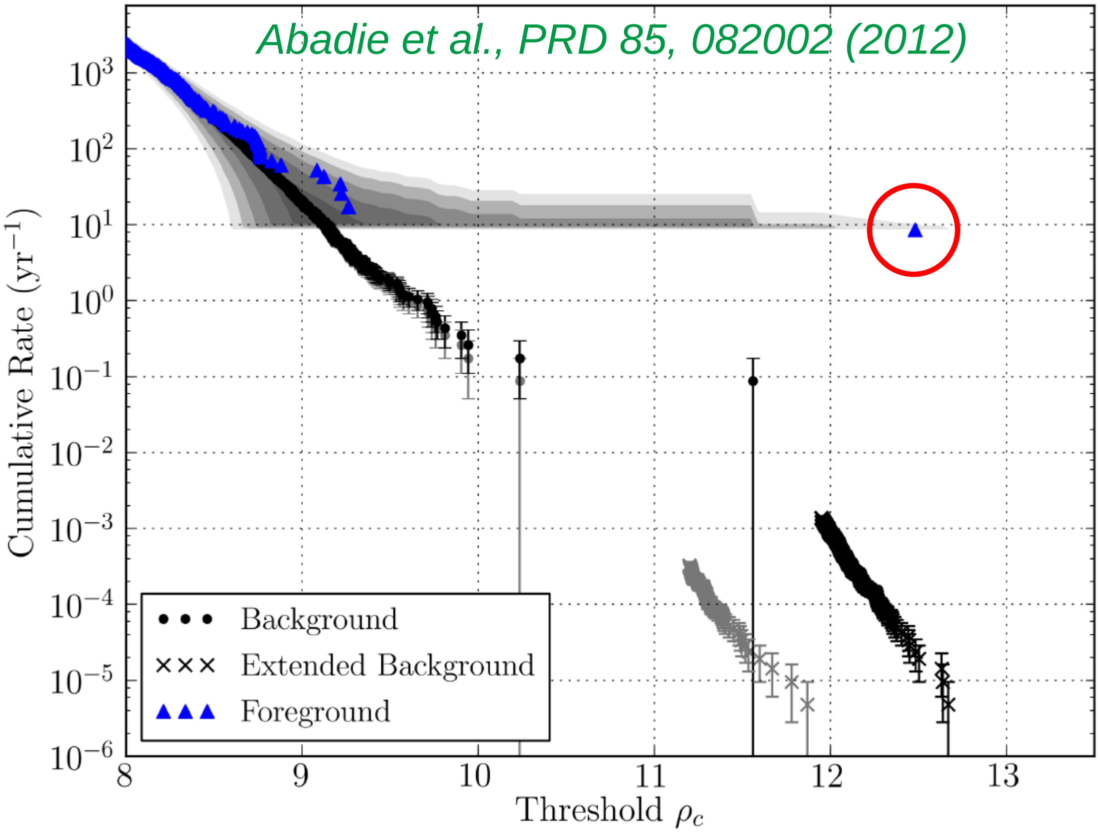


Images taken ASAP, and on subsequent nights

No significant optical transient found in telescope images

Significance of the "Big Dog" Event Candidate

Modest significance in GW burst search,
but highly significant in matched filter inspiral search



Over the winter:

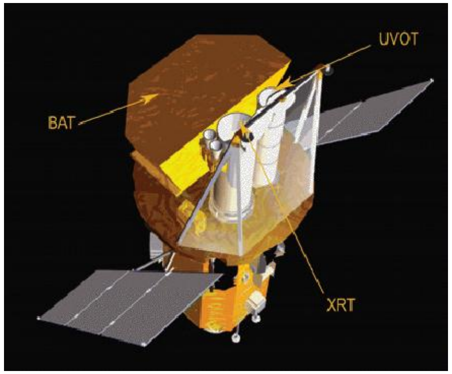
- Refined background estimation techniques – estimated 1 in 7000 y
- Did binary parameter estimation studies
- Wrote and polished a Phys Rev Letter

"Opened the envelope" in March 2011…

It was a blind injection

For more of the story: http://www.ligo.org/news/blind-injection.php

Swift Follow-up Observations



Swift target-of-opportunity observations were executed for two triggers

- One was the Big Dog blind injection
- Other was from the winter running period

Pointed XRT and UVOT exposures taken

- Up to 5 fields per trigger, targeting nearby galaxies
- Additional (reference) images obtained weeks later

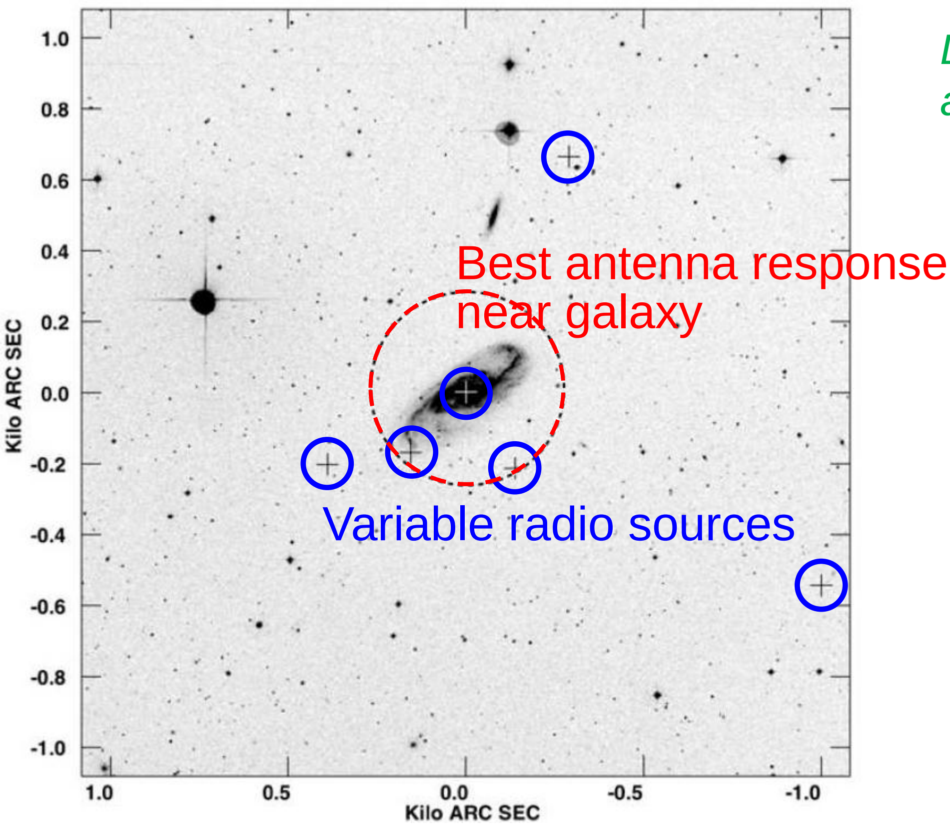
Images analyzed by collaborating Swift scientists

- *Preprint to appear on arXiv soon*

Later Radio Follow-Ups

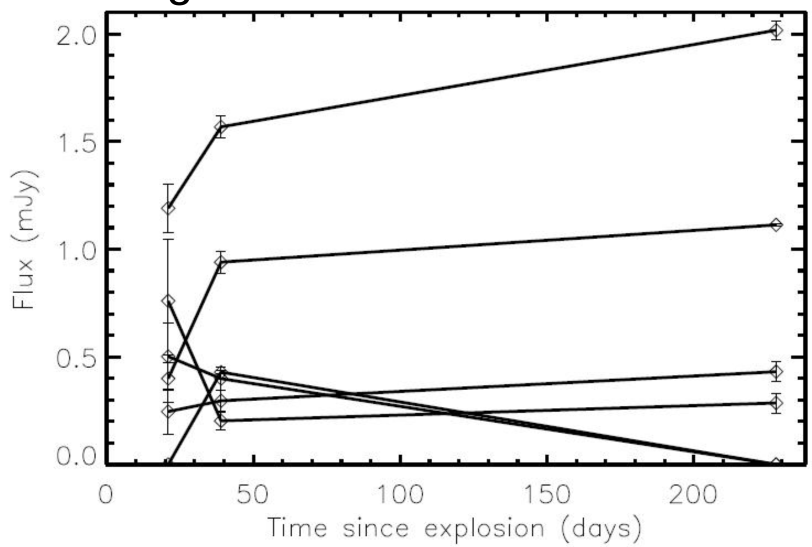
Two GW triggers followed up using the EVLA starting ~3 weeks after the triggers

- Three galaxies imaged for each trigger
- Some variable radio sources found, but consistent with normal population



Lazio, Keating, Jenet, Kassim, LSC & Virgo, arXiv:1203.0093

Light curves for these sources



Optical Image Analysis and Interpretation

Goal: Find an optical transient associated with the GW event candidate

- Present (or brighter) in target image but not in reference image

Two basic approaches explored with current data:

- Object identification followed by comparison of object lists
- Image subtraction followed by object identification

Challenges

- Very large search area – may find artifacts, or unrelated transients
- Optical transients may be on top of galaxy images—harder to identify
- Variations in seeing, camera performance complicate comparisons
- Need good reference images
- How to interpret any candidate transient counterpart (analysis-dependent!)

Image analysis still in progress for some scopes

- Had to obtain reference images; students and postdocs learning the ropes

Ideas for Future EM Follow-up Program

Technical improvements on the GW side

Faster data transfer and event reconstruction

Better position reconstruction, and understanding of uncertainties

Better automated data quality checks – avoid manual validation step ?

Uniform communication protocol with telescopes

Better engagement with astronomers

Open up program to ensure sufficient coverage

- Especially during pre-detection era

Fully engage EM astronomers in planning follow-up observing strategy

- Galaxy bias, repeated observations, coordination, spectroscopy, …

Ensure prompt image analysis and interpretation

- Quickly check for a candidate counterpart to guide further observations

Be prepared to quantify the significance of an apparent counterpart

Issue public alerts after the first few detections

Summary

We've already managed to make some connections between GW and EM observations

- Deeper GW transient searches triggered by astrophysical events
- Deeper continuous-wave GW searches guided by radio/X-ray timing data
- Limited (so far) sharing of GW event candidates for follow-ups in optical, X-ray and radio – proof of principle

There's plenty more to do for the Advanced Detector era

- Continue to search deeply around notable astrophysical events
- Work with radio and X-ray astronomers on guidance for CW searches
- Broaden opportunity for participation in follow-up observations
- Plan observing strategies more deliberately
- Address science issues proactively
  - e.g. significance of apparent EM counterparts

Need to prepare to interpret joint detections !